Accelerated Insertion of Materials – Composites

Presented at

Penn State University

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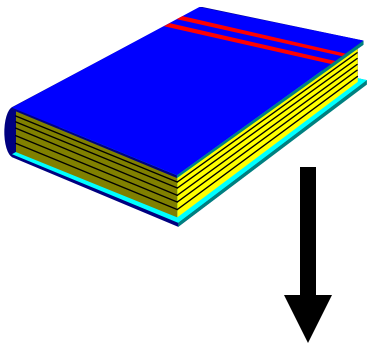
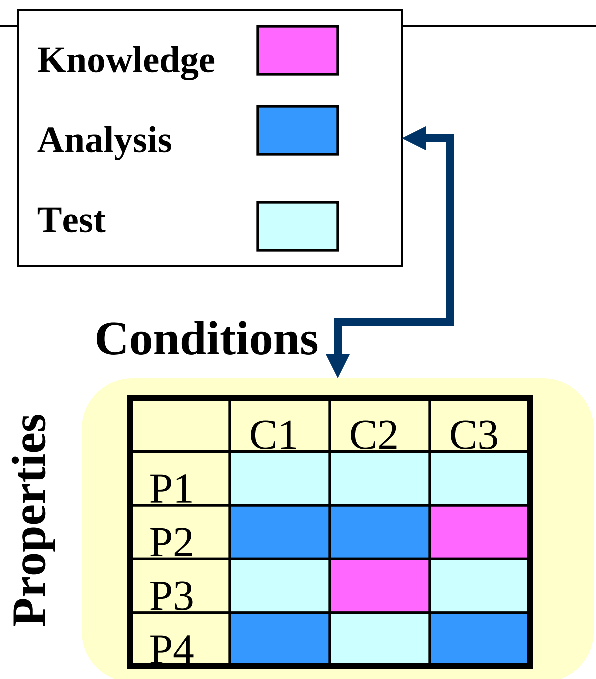
AIM-C Team - Boeing (St. Louis, Seattle, Canoga Park, Philadelphia), Northrop Grumman, Materials Sciences Corporation, Convergent Manufacturing Technologies, Cytec Fiberite, Inc, Massachusetts Institute of Technology, Stanford & NASA (Langley)

Accelerated Insertion of Materials Goals





Designer's View

Each data point has its own "resume"

Transform traditional materials database and qualification practice into an efficient and interactive process fully integrated into the available design tools and design community that retains/improves upon the robustness and reliability of traditional practice.

Use the right source (model, experiment, experience) to fill in the data

Reach for robustness not precision. Know the confidence in the data when needed.

Models can (and will) evolve – confidence in the knowledge of errors and uncertainty is what is needed

The AIM-C Team

- Boeing – Seattle and St. Louis – AIM-C CAT, Program Management
- Boeing – Canoga Park – Integration, Propagation of Errors
- Boeing – Philadelphia – Effects of Defects

CMT

- Convergent Manufacturing Technologies - Processing
- Cytec Engineered Materials – Constituent Materials, Supplier
- Materials Sciences Corporation – Structural Analysis Tools
- MIT – Dr. Mark Spearing – Lamina and Durability
- MIT – Dr. David Wallace – DOME, Architecture
- Northrop Grumman – Bethpage – Blind Validation
- Northrop Grumman – El Segundo – Producibility Module
- Stanford University – Durability – Test Innovation

Outline

- Introduction to AIM
  - Why AIM is Important
  - Technical Approach
  - Modeling Architecture
  - Methodology
  - Designer Needs
- Sample Problem 1
  - Cure Hardening Behavior of Epoxy
- Sample Problem 2
  - A Zero CTE Laminate
- Sample Problem 3
  - Cure Cycle Development
  - Processing Properties
  - Exotherm
  - Residual Stresses
- Design of Complex Structure
  - Hat Stiffened Panel
- Conclusions/Summary

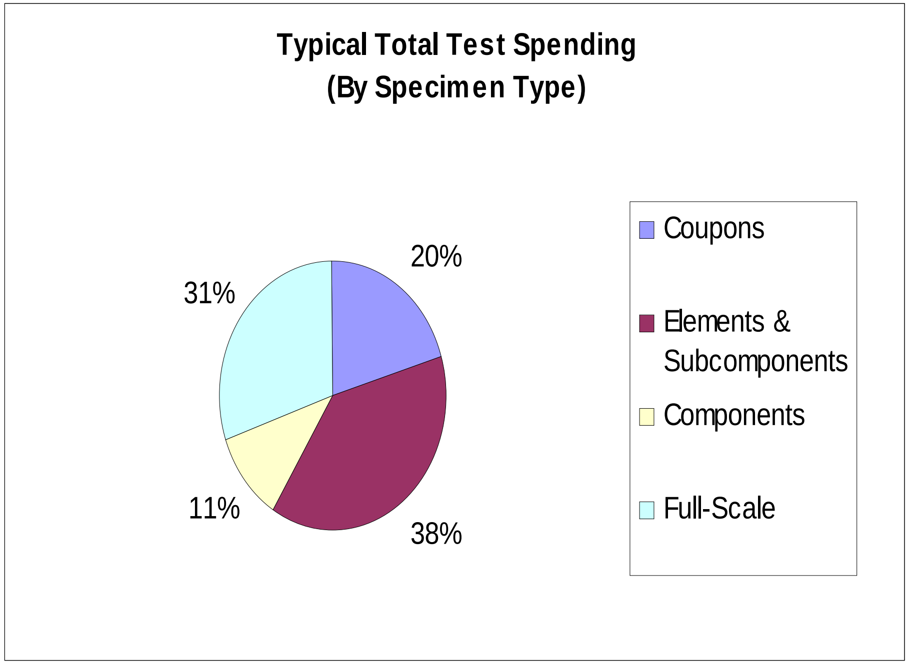
Understanding the Current Process
Why We Test

- Using an Un-augmented "Building Block Approach", a Typical Composites Program Requires 6000 to 10,000* Specimens to:
  - Characterize the Material
  - Develop Design Allowables
  - Select/Develop the Design Concept
  - Calibrate Semi-Empirical Analysis Methods
  - Validate the Design and Analysis

* Ref. F/A -18 and 777 empennage

How Much It Costs

- The Total Cost of Building and Testing These Specimens is between $50M and $100M and takes at least several years.
- Despite several very expensive component tests, much of this money and time is spent on the numerous coupons, elements, and subcomponents.



•Specimen types and numbers are averages based on various test plans

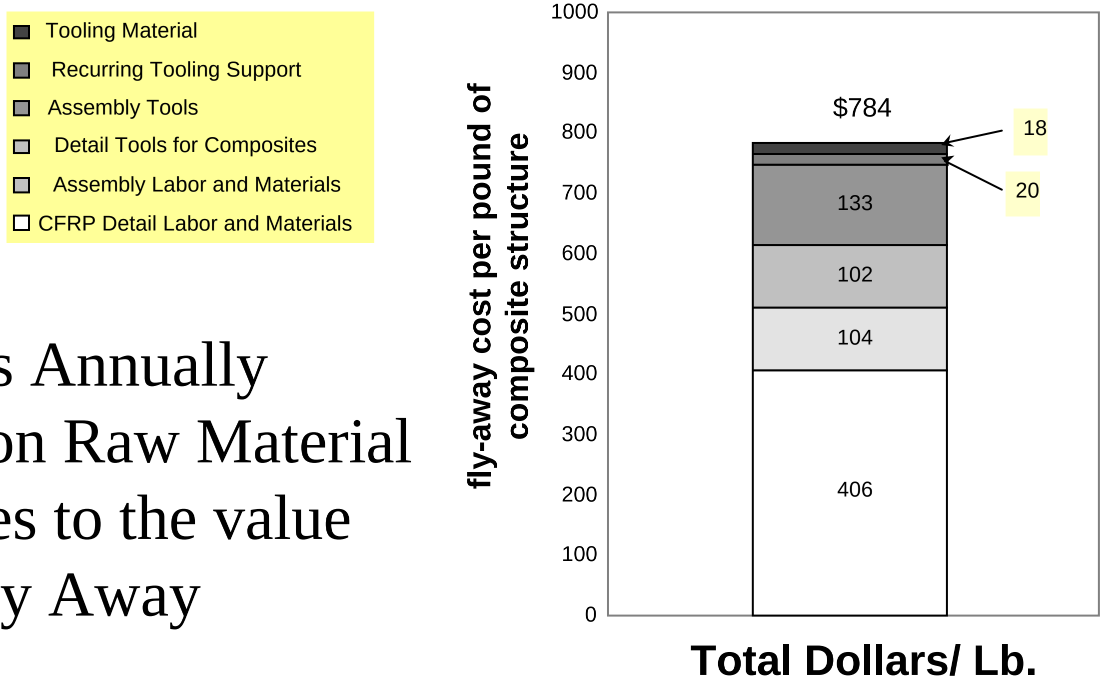
- **New composite material specimens only**
- **Only 1 full-scale Test Component testing includes items such as fuel box, side-of-body joint, large fittings, etc.**

• Fab. And Test Hours/specimen (for each type) based on internal Boeing estimating documents

•Typical Industry Labor Rates

• Fabrication and Test Cost Only –Facilities, Equipment, Material, and Design/Analysis Costs not included

Boeing is the World's Largest Manufacturer of Composite Aerospace Parts



- 4 Million Pounds Annually
- ~ $300M Spent on Raw Material
- We Add ~ 5 times to the value
- $2B Annually Fly Away

The AIM Process Uses IPT Lessons Learned to Drive Rapid Insertion

Conventional Building Block Approach to Certification

Application Requirements
3 Months

Target Properties
3 Months

Supplier Offerings
3-6 Months

Trade Studies
2-6 Months

Fabrication Studies
2-6 Months

Allowables Development
6-18 Months

Critical Details Fab & Test
2-6 Months

Subcomponent Fab & Test
2-6 Months

Component Fab & Test
2-6 Months

Full Scale Fab & Test
12-24 Months

Time Reduction

Cost Reduction

Risk Reduction

The AIM Focused Approach to Certification

Application Requirements
3 Months

Trade Studies
3 Months

Supplier Offerings
3-6 Months

Target Properties
2-6 Months

Design Features
2-6 Months

Manufact. Features
3-6 Months

Key Features Fab & Test
2-6 Months

Allowables Development
4-9 Months

Risk Reduction Fab & Test
4-9 Months

Full Scale Fab & Test
12-24 Months

35% Reduction in Total Time to Certification
45% Reduction in Time to Risk Reduction

BOEING®

AIM Accelerated Insertion of Materials

AIM Methodology: Criteria for Success

1. **Architecture**
   - Open/controlled (secure/open)
   - Platform independent (Intranet vs. Internet)
2. **Capabilities – at least 4 capabilities/modules**
   - Properties – time dependent properties
   - Durability/Lifing
   - Processing/Manufacturing/Producibility
   - Cost

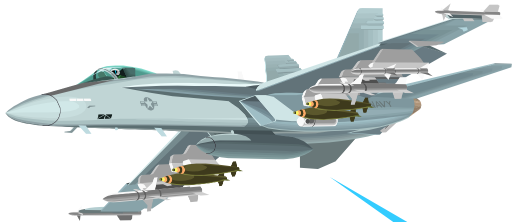
AIM Methodology: Criteria for Success

3. **Features/Outputs**

- Demonstrate that the methodology reproduces the DKB
- Demonstrate that “a rogue” process spec will result in a flag by the system
- Demonstrate that a rogue “geometry” results in an “un-producible” flag
- Demonstrate the ability of the system to direct experiment – to direct an experiment to determine a “benchmarking” parameter, or a basic physical quantity. (validation/calibration)

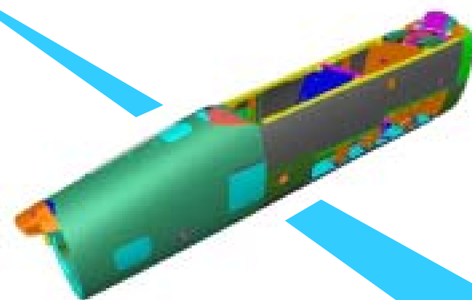
DESIGN TEAM'S NEEDS
Requirements Flow-Down

Program/Product Level



- Performance
- Life Cycle Cost
- Development and Delivery Schedules
- Risk Posture

Component Level



- Weight, Smoothness, etc.
- Service Environment
- Unique Functionality
- Unit Cost Targets
- Production Concept
- O&S Concepts

Part Level

- Strength and Stiffness
- Temperature
- Geometry Assurance
- Fab and Assembly Concepts
- Damage Tolerance & Repair

Material Choice is Influenced by Higher Level Requirements (and Vice Versa)

DESIGN TEAM'S NEEDS
High Priority Requirements

Structural

- Strength and Stiffness
- Weight
- Service Environment
  - Temperature
  - Moisture
  - Acoustic
  - Chemical
- Fatigue and Corrosion Resistant

Manufacturing

- Recurring Cost, Cycle Time, and Quality
- Use Common Mfg. Equipment and Tooling
- Inspectable
- Machinable
- Automatable
- Impact on Assembly

Supportability

- O&S Cost and Readiness
- Damage Tolerance
- Inspectable on Aircraft
- Repairable
- Maintainable
  - Depaint/Repaint
  - Reseal
  - Corrosion Removal
- Logistical Impact

Material & Processes

- Feasible Processing Temperature and Pressure
- Safety/Environmental Impact
- Useful Product Forms
- Raw Material Cost
- Availability
- Consistency

Miscellaneous

- Observables
- EMI/Lightning Strike
- Supplier Base
- Applications History
- Certification Status
  - USN
  - USAF
  - FAA

Inadequate Data or Performance in Any of These Areas Will Jeopardize the Potential Application

DESIGN TEAM'S NEEDS
Data Drives Decisions

- **Are Current Materials, Designs, and Methods Capable of Meeting Needs?**

NO →

- **Are Current Materials Capable of Meeting Needs (with changes to design and/or methods)?**
  - **YES** ↓ **Change Design and/or Methods**
  - **NO** ↓ **Pursue New Material**

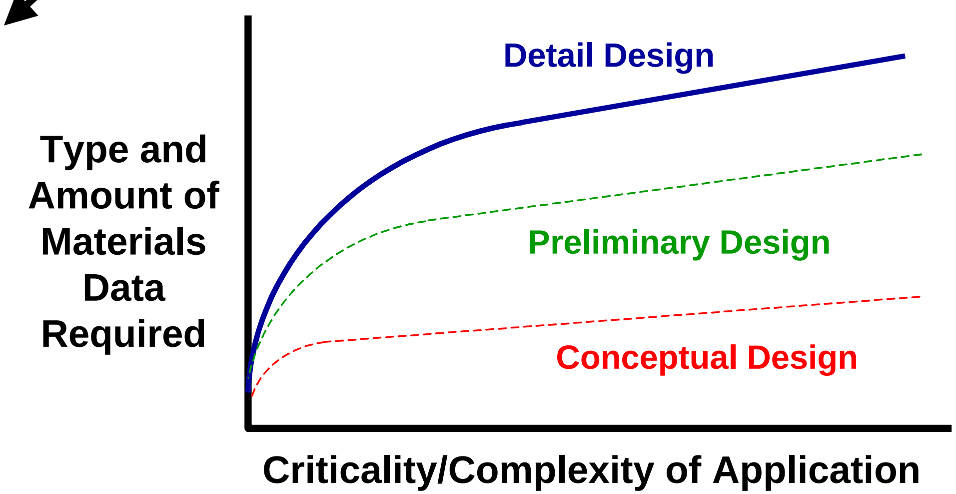
YES ↓

- **Is Program/Customer Willing to Invest in New Materials for Performance Improvement?**

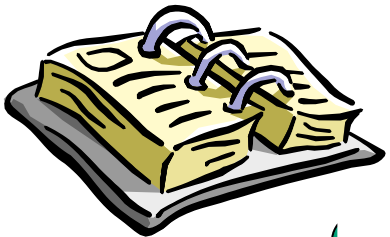
YES ↓

Pursue New Material

Materials Development Effort



AIM-C Will Validate the Process



Methodology
That Links an Accelerated Process to the Knowledge Requirements

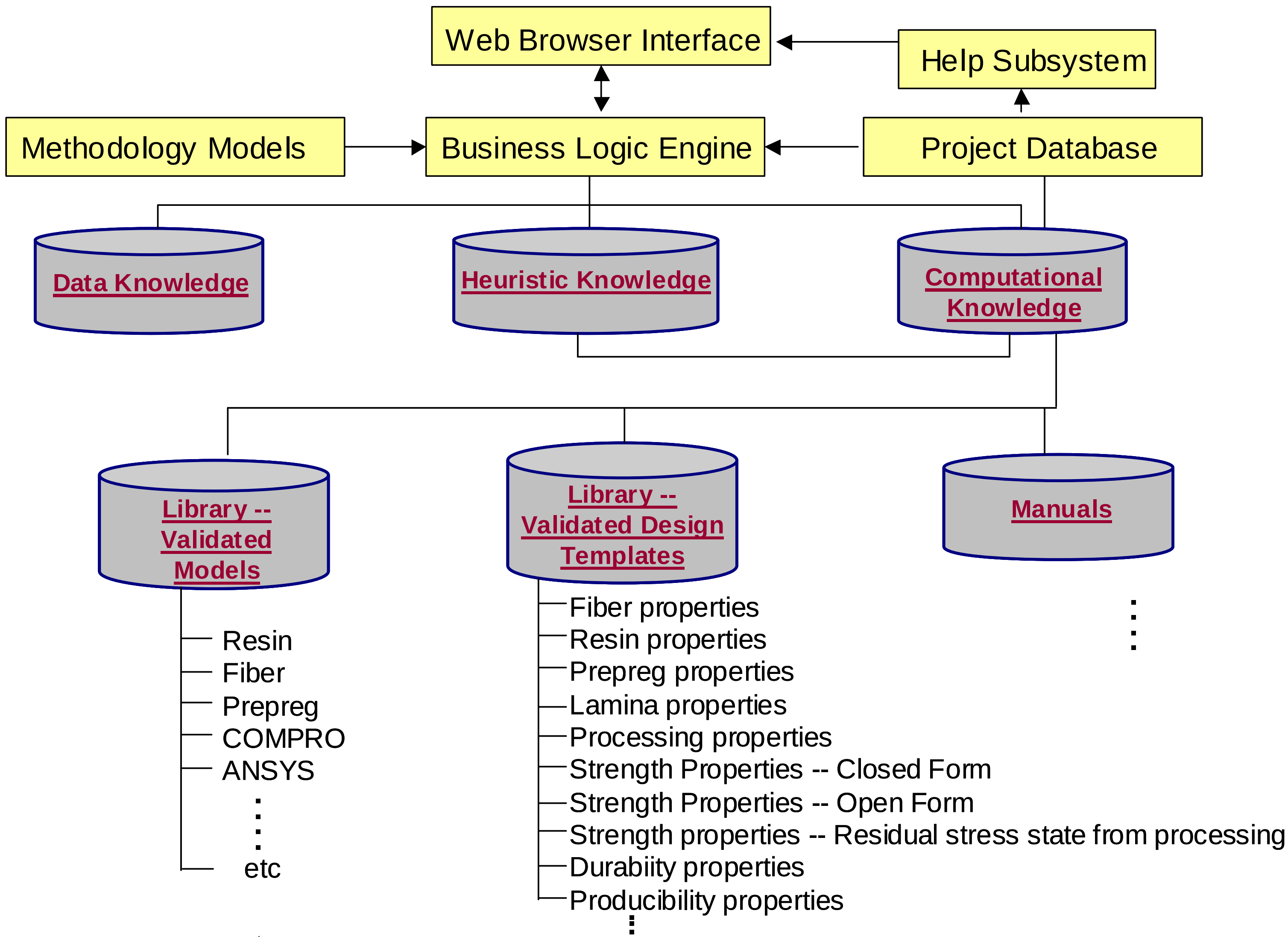
Embedded In

Software
That Links the Methodology to Knowledge, Analysis Tools, and Test Recommendations

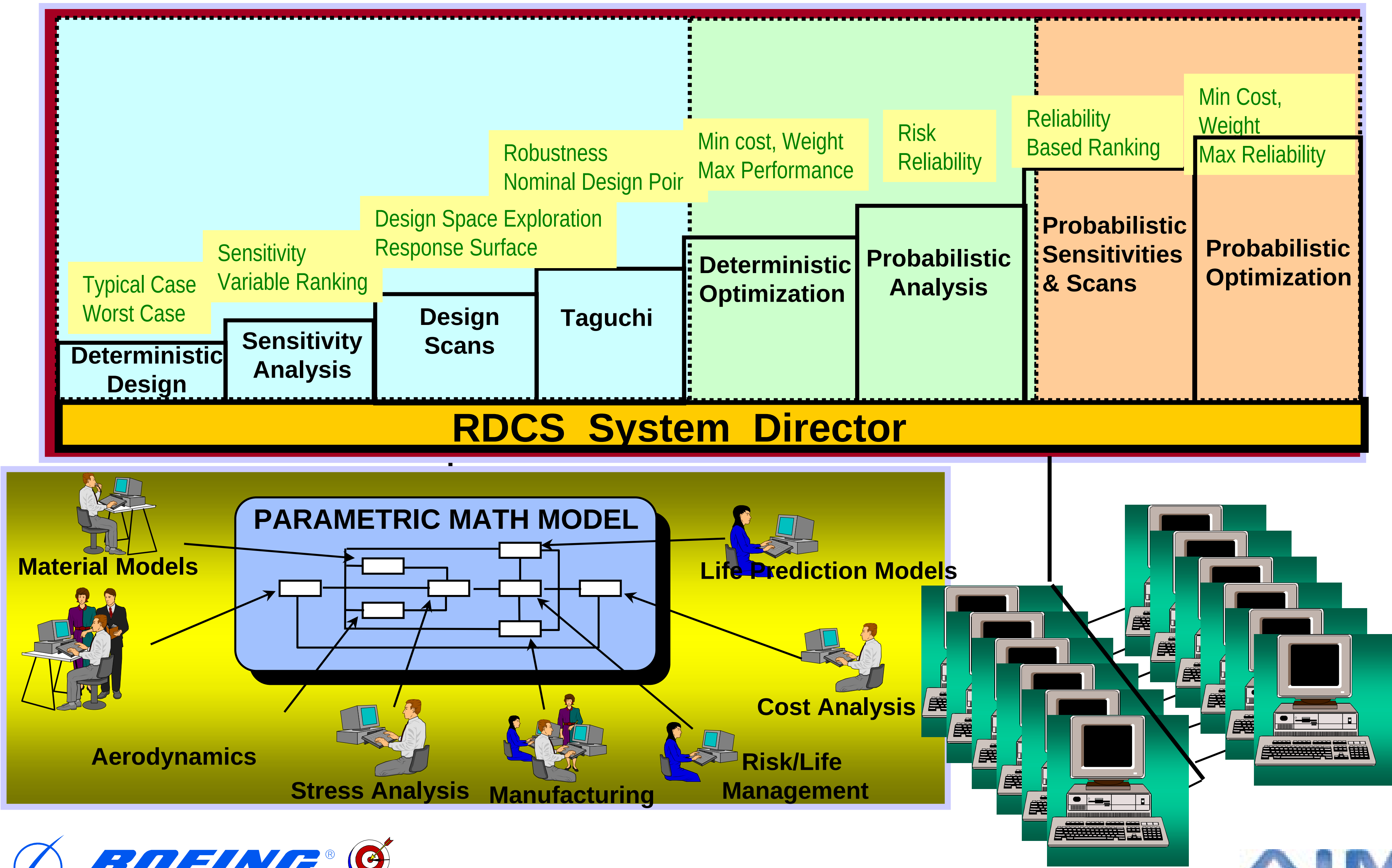
Validated By

Demonstrations
Focused on Recreating Existing Data, Precluding Persistent Problems, and Independent Peer Assessment

AIM-C Software Architecture

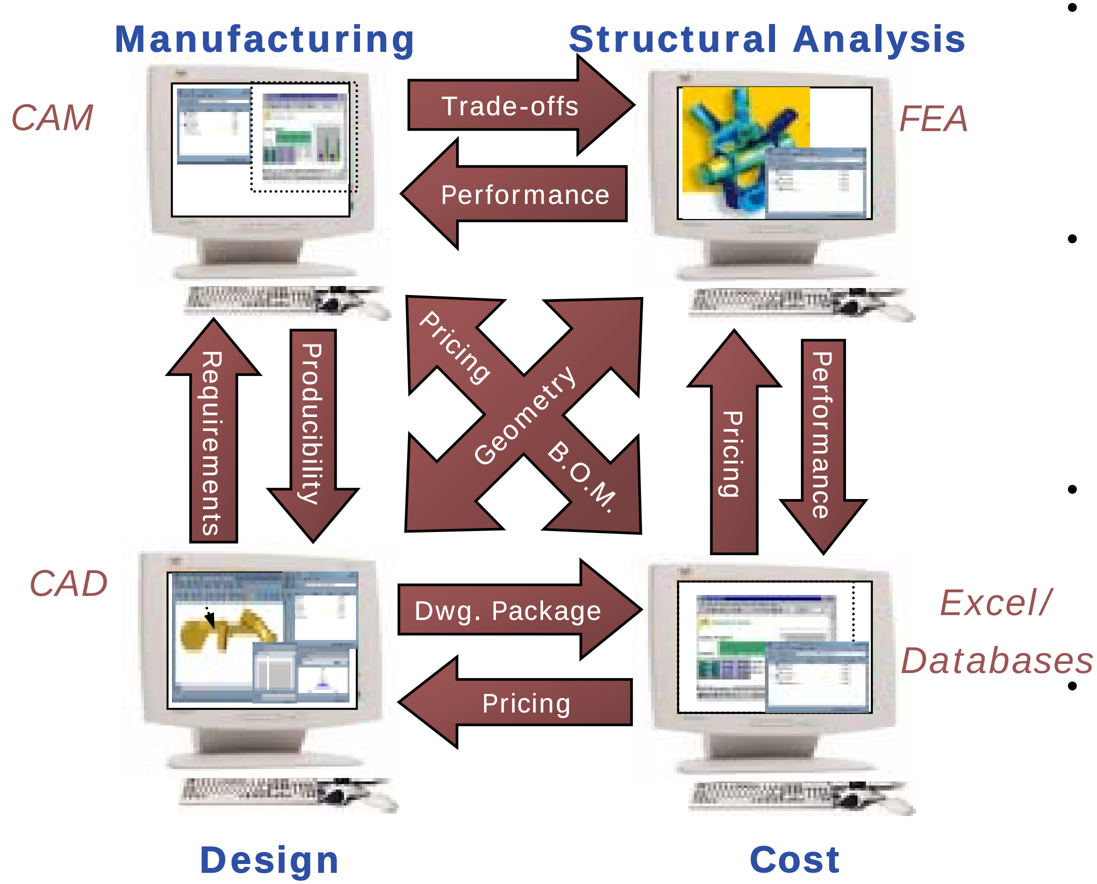


Robust Design Computational System



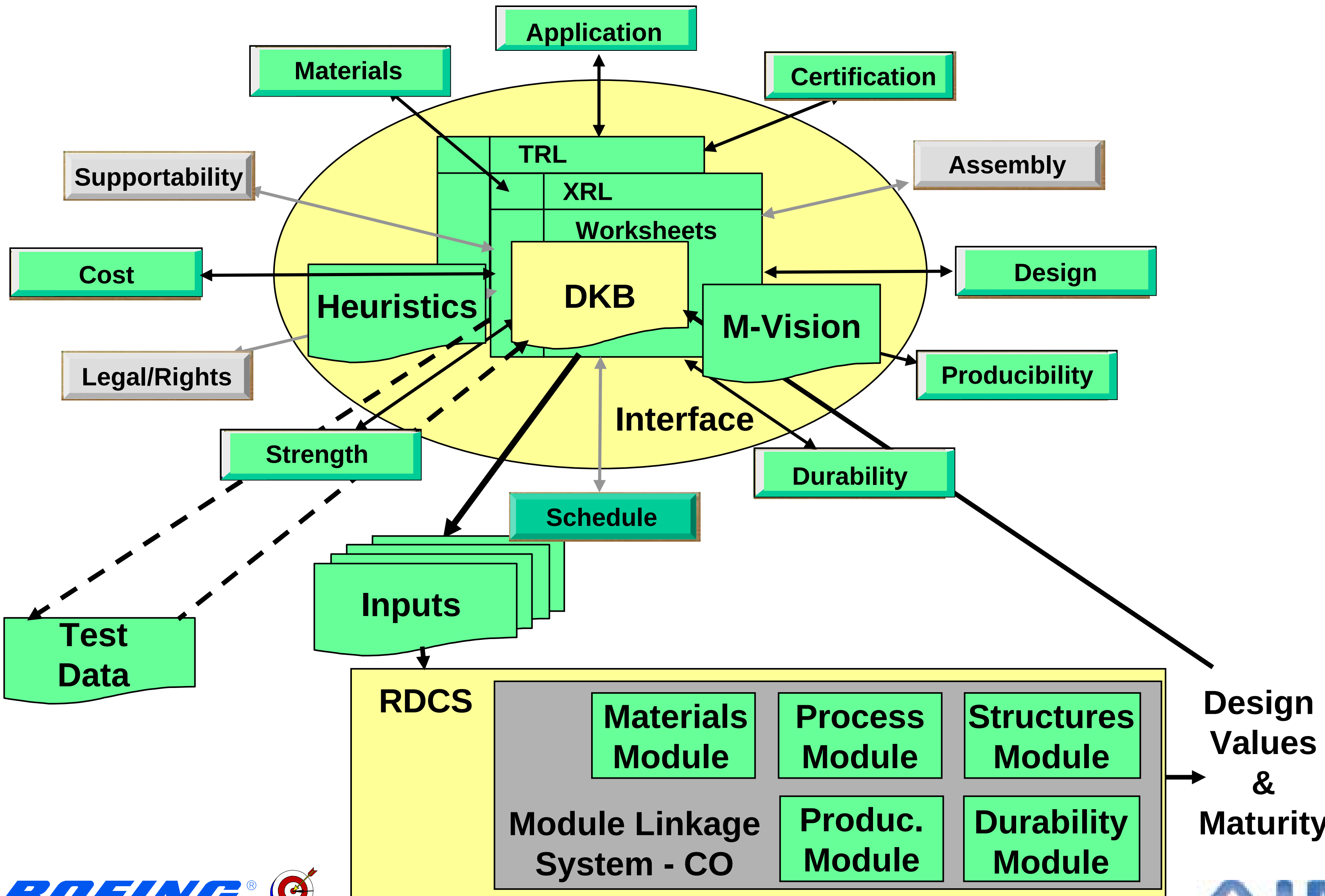
The Oculus Integration System

CO™: A Plug & Play Modeling Environment

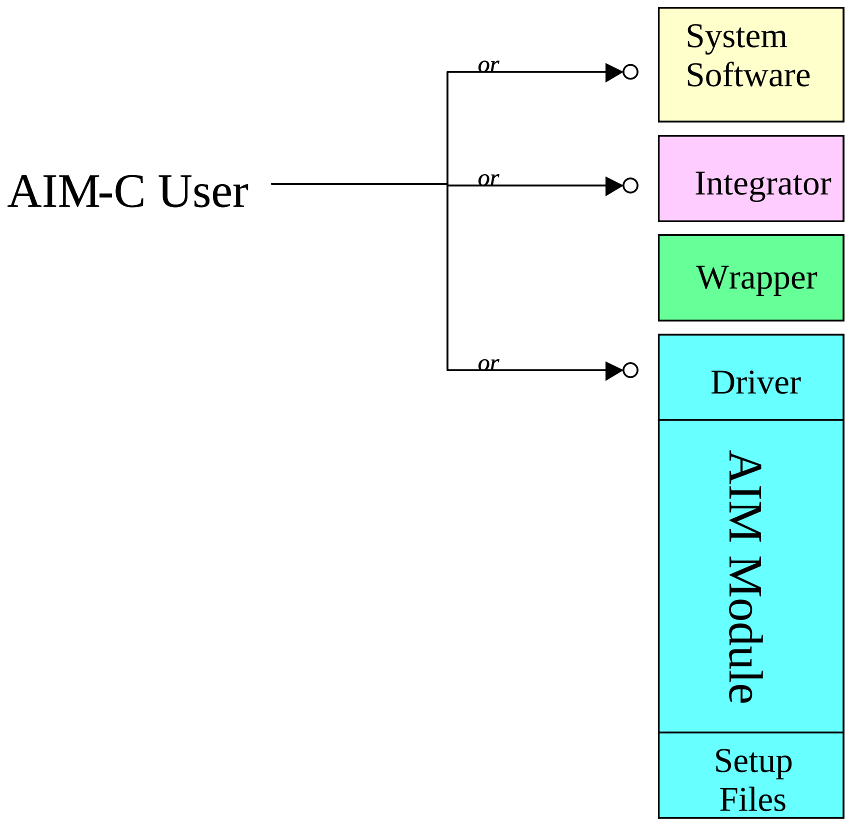


- **Integrates Data and Software Applications on-the-fly**
  - Drag & Drop, Plug & Play
  - Simple to create, modify, manage, maintain
- **Enables Real-time data sharing between applications**
  - Secure
  - Controlled
  - Intra/Internet
- **Platform Independent**
  - Distributed
  - Neutral to Platforms and Applications
- **Increases Value of Previous Investments**
  - Software
  - Hardware
  - Networks

AIM-C System Vision



The User Is Able to Run the Module At *Three* Different Levels



1. Through the System Software
2. Through the Integration Software

3. *For trouble-shooting, and validation, the individual modules can be ran directly from a driver program.*

Technical Components

of AIM-C

Materials Insertion Methodology

Baseline Material and Structure

Modular Approach to Modeling

- Prediction of Structural Response
  - Composite Mechanical Properties, including
  - Progressive Damage Failure, and
  - Durability
- Distributed Object-based Modeling Environment (Oculus CO)
  - An *emergent* network of models (information services)
- Robust Design Computational System (RDCS)
  - Distributed computing capability
  - Uncertainty and Error Propagation
  - Probabilistic Analysis
- Materials, Processing, Producibility and Manufacturing $(M\&P)^2$
  - Raw material physical and mechanical properties
  - Residual stress state as dependent on processing
  - Producibility aspects of new materials and structure

Validation

Design, Certification, Implementation Considerations

Near Term or Current Capabilities

1. Processing Module
   - Processing Window Studies
   - Spring-In and Deformation Calculations
   - Evaluation of Novel Processes (i.e. staging, VaRTM)
   - Thick Laminate Structure
2. Structures Module
   - Stiffener termination/pull off problem
   - OHC, OHT, Un-notched Coupon Prediction
   - Large Notch Type Damage Problem
3. Robust Design Computational System (RDCS)
   - Already in use by Boeing Programs
   - Combined Structure/Processing Effects -- Microcracking
   - Sensitivity Analysis/Design Space Scans, Optimization, etc.
4. Qualification/Re-qualification of Materials

Sample Problem 1

Epoxy Cure Hardening Behavior

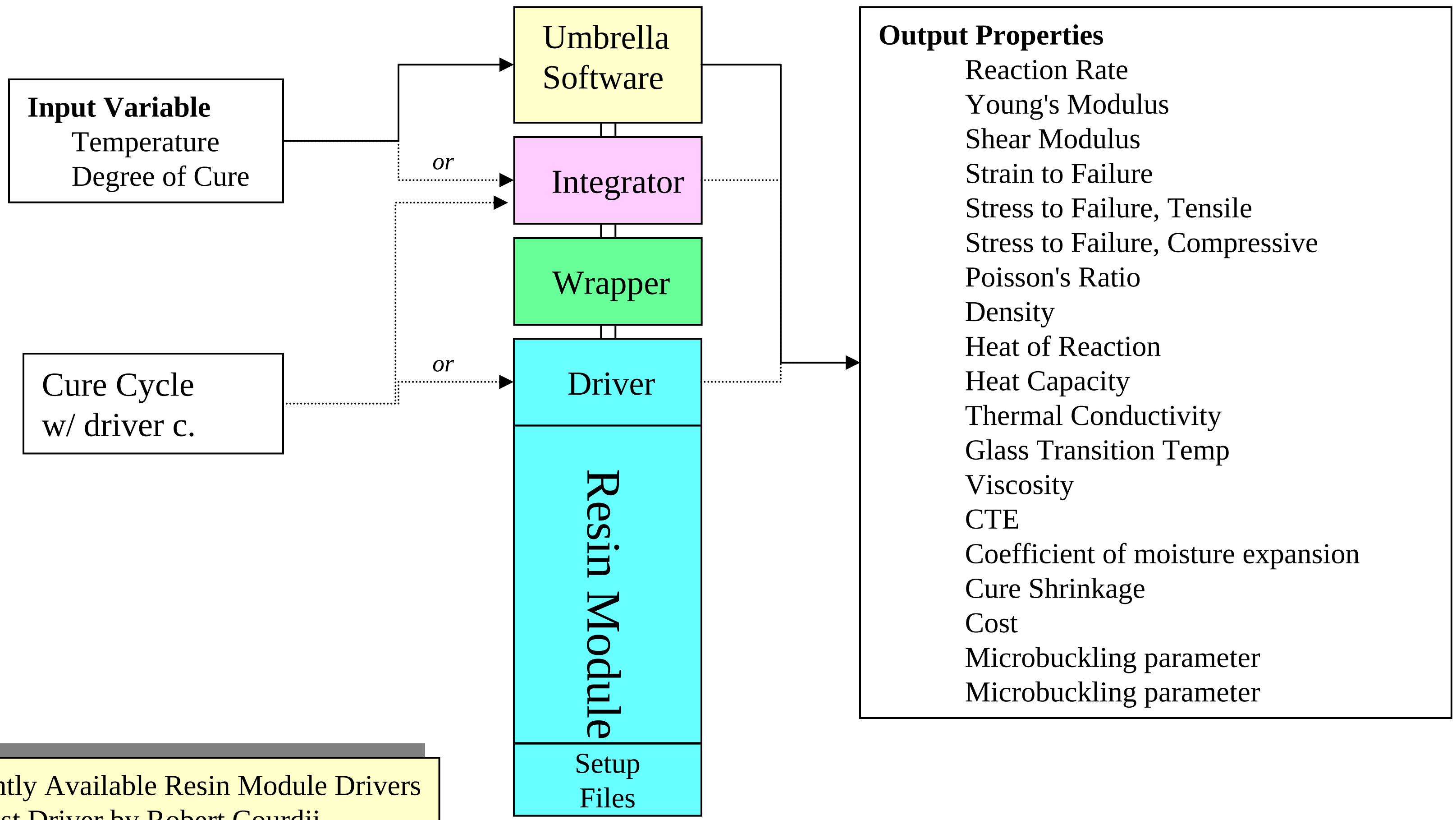
Problem Statement

- What is the cure-hardening behavior of a resin
- When does it reach minimum viscosity, gel, vitrify, and what is the glass transition temperature for a given cure cycle

Simulate the cure behavior of the resin

Architecture

Resin Module

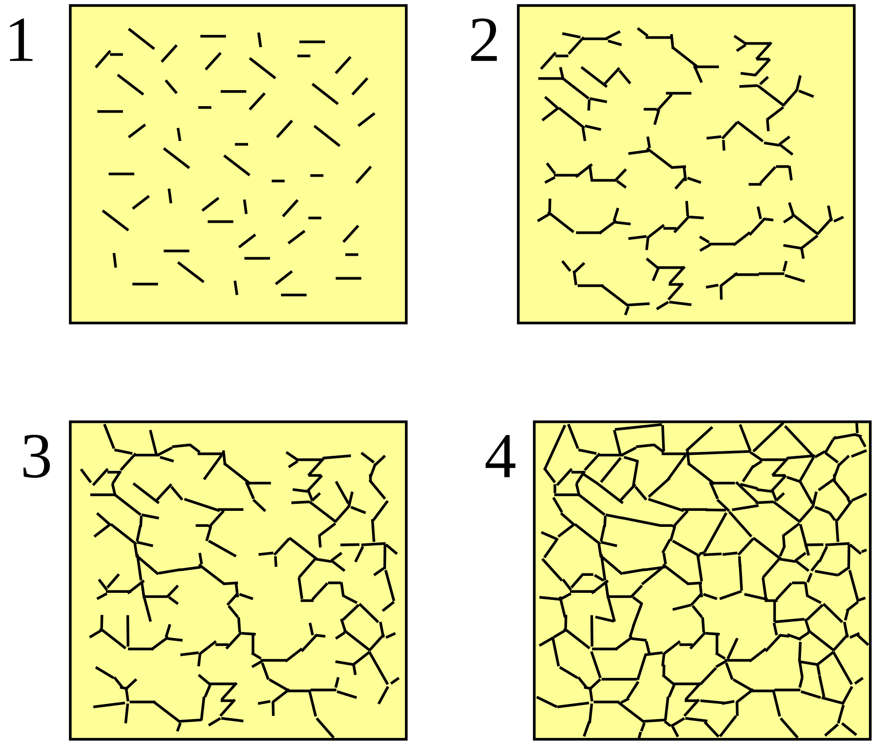


Currently Available Resin Module Drivers

a. Test Driver by Robert Courdji
b. DLL driver by Robert Courdji
c. Integrator driver by Karl Nelson
d. Ben Koltenbah Driver

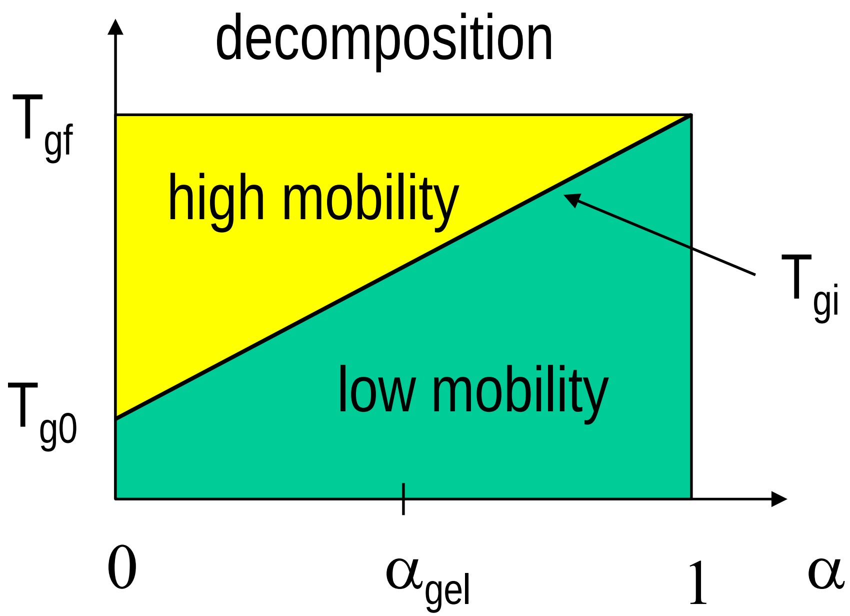
Curing of a High Performance Epoxy

- Constituents
  - Prepolymer
  - Curing agent
  - Catalysts
- Important events
  - Gelation
    - Onset of 3D network
  - Vitrification
    - Glassy behavior



Vitrification

- $T_g = T_g(\alpha)$
- $T < T_g(\alpha)$ => large reduction of resin free volume



State Variables in Processing

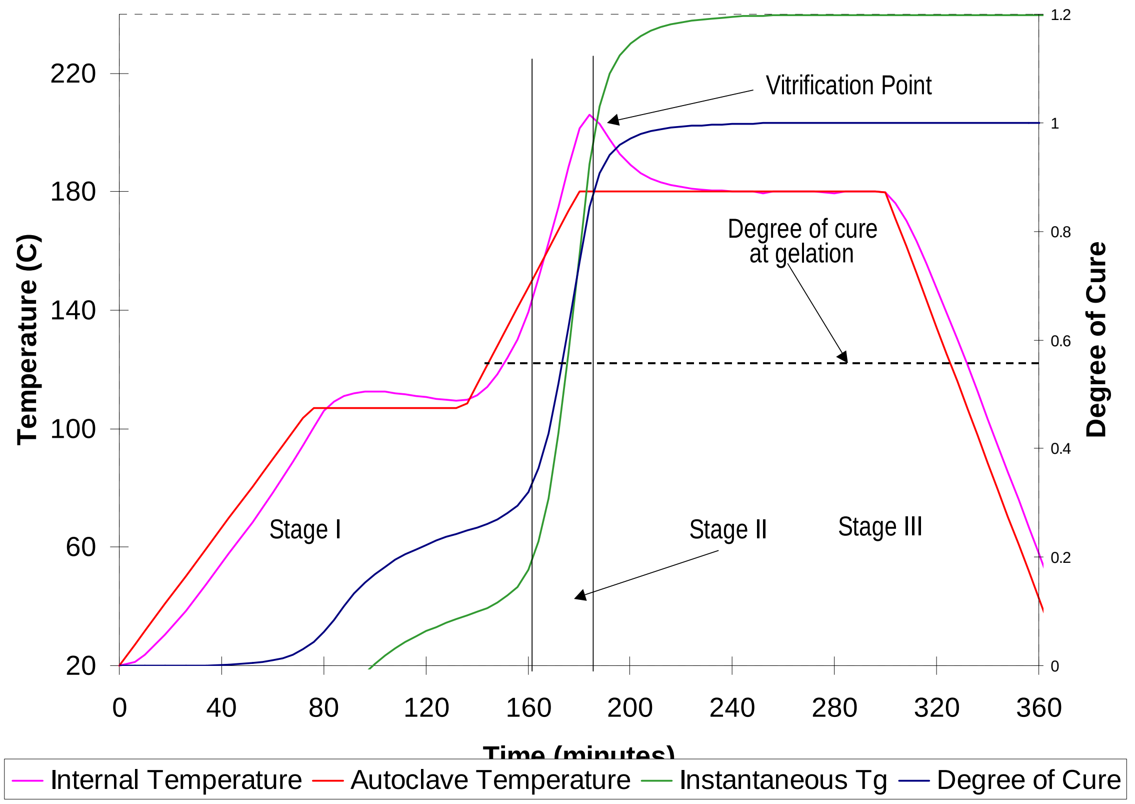
- α: degree of cure
- T: temperature
- All properties dependent on α and T:
  - Mechanical (α,T)
    - viscosity, modulus
  - Physical (α,T)
    - thermal expansion, cure shrinkage
  - Thermal (α,T)
    - thermal conductivity, specific heat

Viscosity and Modulus Development

Stage I: Viscous behavior, $\alpha<\alpha_g$, $T>T_g$

Stage II: Visco-elastic behavior, $\alpha>\alpha_g$, $T>T_g$

Stage III: Elastic behavior, $\alpha>\alpha_g$, $T<T_g$



Resin Module Simple Demonstration

Ran in Isolation of Other Modules

Output to Text File to Excel

CureCycle.DAT - Notepad

File Edit Format Help

```
;Cure Cycle Set Up File For Testing the Resin Module
;English units version
;
; Note: the semicolon ";" in the first column identifies
;              the beginning of a comment. All other lines are data.
;
;
;Version
; "01/30/02kmn"
;
;The number of ramp - hold segments
 3
;
; Starting Degree of Cure and Temperature (C)
 0.010, 22.0
;
;Segment No. 1
;Ramp Rate (C/min), Target Temp (C), and Hold time (min)
 1.0,  122.0, 1.0
;
;Segment No. 2
;Ramp Rate (C/min), Target Temp (C), and Hold time (min)
 1.0, 179.5, 360.0
;
;Segment No. 3
 -2.0, 22.0, 1.0
;
;End of File
```

Execute Resin Module

Resin_977_Ver-25Nov-2001.txt - Notepad

File Edit Format Help

```
//Defining the unique ID for the file but need to find a way to verify its
uniqueness
         //For now it is omitted until we can find a way.
  //ResinMatConstFileID = <Maybe a path to a local file?>
// file name or full path on MS windows (UNIX can use relative path)

CreatedBy = Karl Nelson, Boeing Phantom Works
ModifiedBy = Pete George, Boeing
Date = Feb 25, 2002
Version = Beta 1.1
//The above info is not used by the resin module, and will be added in the future.

// The UserInputFile may be omitted by default the Request units are SI and the
DistributionLocation is 0.5 of Type Default
UserInputFile = Resin_977_ver_25Nov-2001_User_Input.txt



//==========================================================================
--------------------------------------------------------------------
// Density
StartProperty = ResinDensity

ModelID =  Constant
ModelDim = 1
DefaultValue = 1.290E+03                    //mean

//The units line may be omitted by default no units are used
DefaultUnits = kg/m^3  //SI=kg/m^3  OR Imperial = lb/ft^3

//The Default distribution model is the distribution to be used when a user wants
to use the distribution of the actual
// property. The other way (Local Distribution Model) is for the user to use a
distribution for each of the material constants that
// make up the material property. If no Distribution Model is given (Default
and/or Local), a Noraml distribution will be used with
// a Std dev of 0.0

Default Distribution Model = Normal

//Std dev
Default Distribution Model Const =  0.005        // g/cm^3 Same units as the
DefaultUnits if not defined
Default Distribution Model Const units = g/cm^3

//NOTE: You can have more then one line of validation comments
ValidationComments = Values from Pete e-mail Oct 12 2001


//Data Section
Const1D = 1.290E+03     //NomResinDensity at DOC=1.0
//The units line may be omitted by default none units are used
```

977-3 Property Values
ResinMainVKMN by Karl M. Nelson Jan. 30, 2002
Boeing Accelerated Insertion of Materials - Comoposies

Time	Temp	DOC	E	G	BulkK	Nu	StrainToFailT	StrainToFai
9.6000E+01	2.3600E+01	1.0002E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
1.9200E+02	2.5200E+01	1.0005E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
2.8800E+02	2.6800E+01	1.0008E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
3.8400E+02	2.8400E+01	1.0011E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
4.8000E+02	3.0000E+01	1.0015E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
5.7600E+02	3.1600E+01	1.0019E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
6.7200E+02	3.3200E+01	1.0024E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
7.6800E+02	3.4800E+01	1.0030E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
8.6400E+02	3.6400E+01	1.0037E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
9.6000E+02	3.8000E+01	1.0044E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
1.0560E+03	3.9600E+01	1.0053E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
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1.2480E+03	4.2800E+01	1.0073E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
1.3440E+03	4.4400E+01	1.0085E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
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1.5360E+03	4.7600E+01	1.0115E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
1.6320E+03	4.9200E+01	1.0132E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
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1.8240E+03	5.2400E+01	1.0174E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
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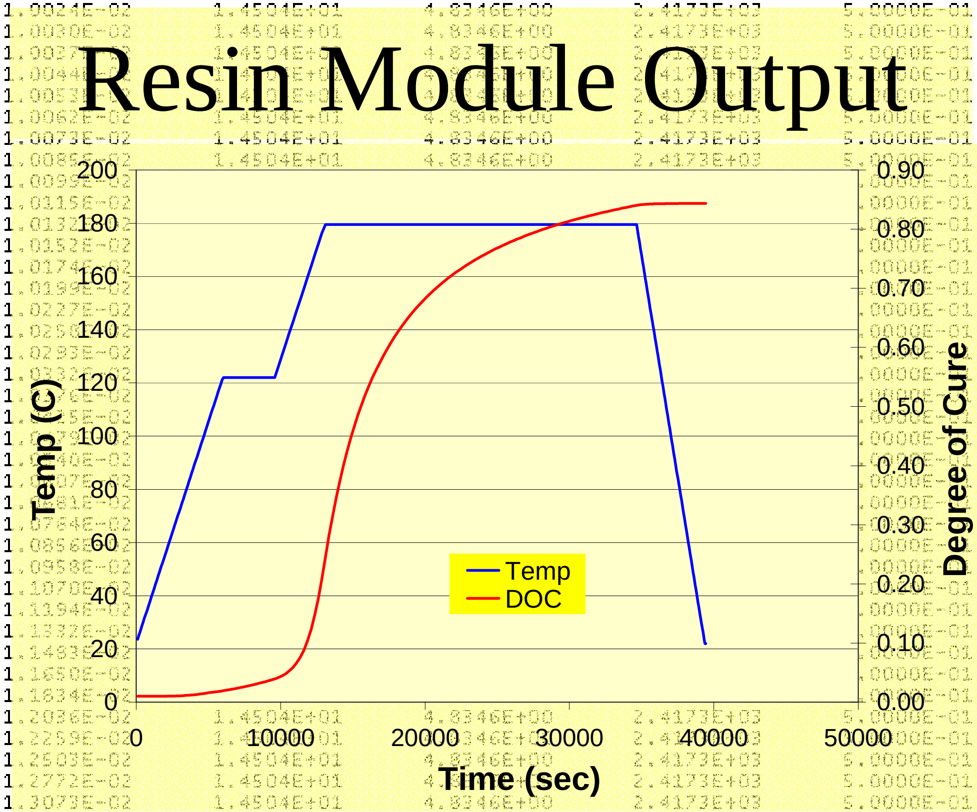
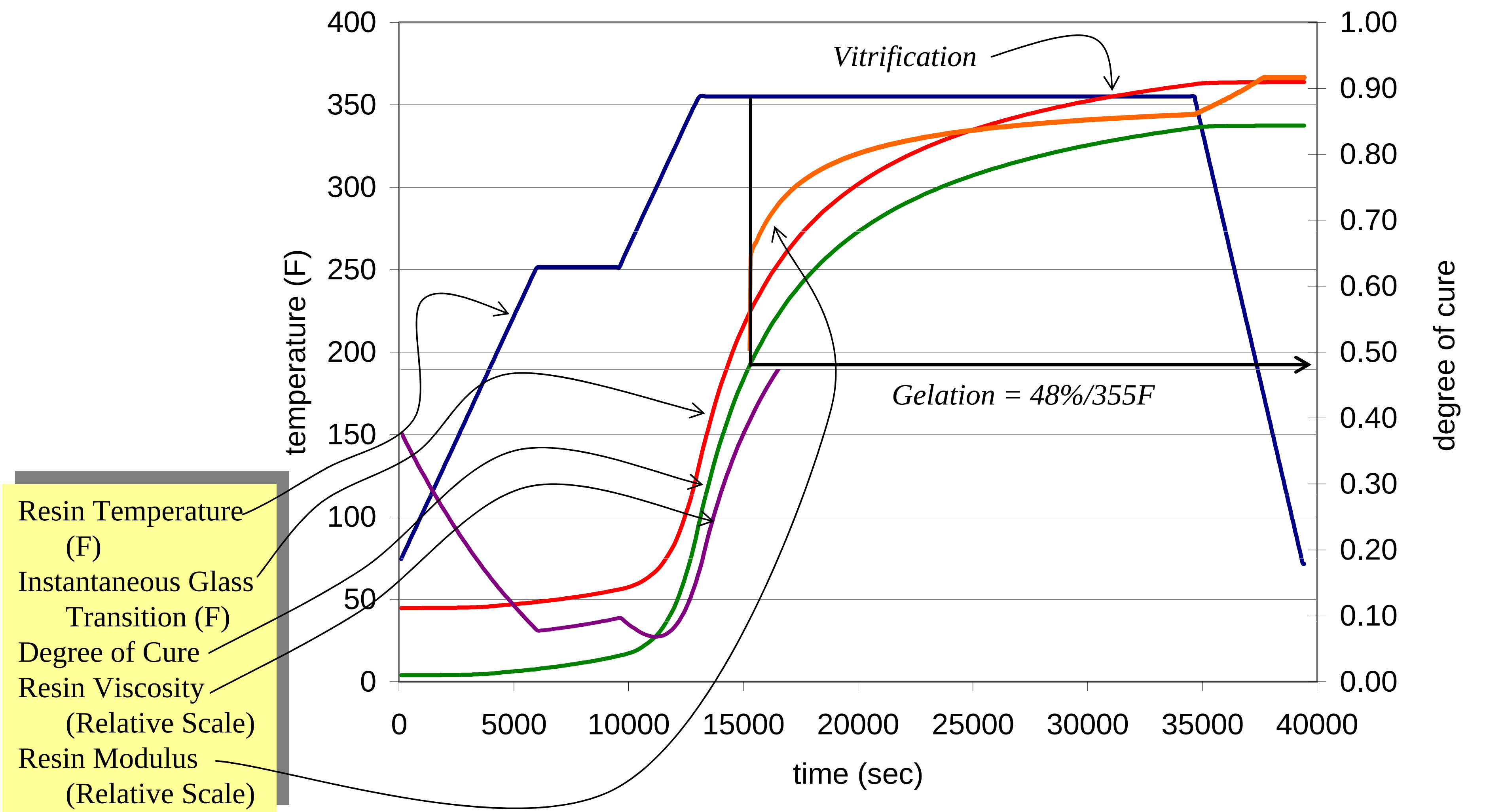
2.0160E+03	5.5600E+01	1.0227E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
2.1120E+03	5.7200E+01	1.0258E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
2.2080E+03	5.8800E+01	1.0293E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
2.3040E+03	6.0400E+01	1.0332E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
2.4000E+03	6.2000E+01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
2.4960E+03	6.3600E+01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
2.5920E+03	6.5200E+01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
2.6880E+03	6.6800E+01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
2.7840E+03	6.8400E+01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
2.8800E+03	7.0000E+01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
2.9760E+03	7.1600E+01	1.0764E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
3.0720E+03	7.3200E+01	1.0856E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
3.1680E+03	7.4800E+01	1.0958E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
3.2640E+03	7.6400E+01	1.1070E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
3.3600E+03	7.8000E+01	1.1194E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
3.4560E+03	7.9600E+01	1.1332E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
3.5520E+03	8.1200E+01	1.1483E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
3.6480E+03	8.2800E+01	1.1650E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
3.7440E+03	8.4400E+01	1.1834E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
3.8400E+03	8.6000E+01	1.2036E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
3.9360E+03	8.7600E+01	1.2259E-02	[illegible]	[illegible]	[illegible]	[illegible]	2.6600E-02	2.6600E-
4.0320E+03	8.9200E+01	1.2503E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
4.1280E+03	9.0800E+01	1.2772E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
4.2240E+03	9.2400E+01	1.3073E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
4.3200E+03	9.4000E+01	1.3414E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
4.4160E+03	9.5600E+01	1.3797E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
4.5120E+03	9.7200E+01	1.4174E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
4.6080E+03	9.8800E+01	1.4528E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
4.7040E+03	1.0040E+02	1.4862E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
4.8000E+03	1.0200E+02	1.5183E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
4.8960E+03	1.0360E+02	1.5495E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
4.9920E+03	1.0520E+02	1.5798E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
5.0880E+03	1.0680E+02	1.6098E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-
5.1840E+03	1.0840E+02	1.6397E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-



Resin Module Output

Gelation Occurs at the Cure Temperature

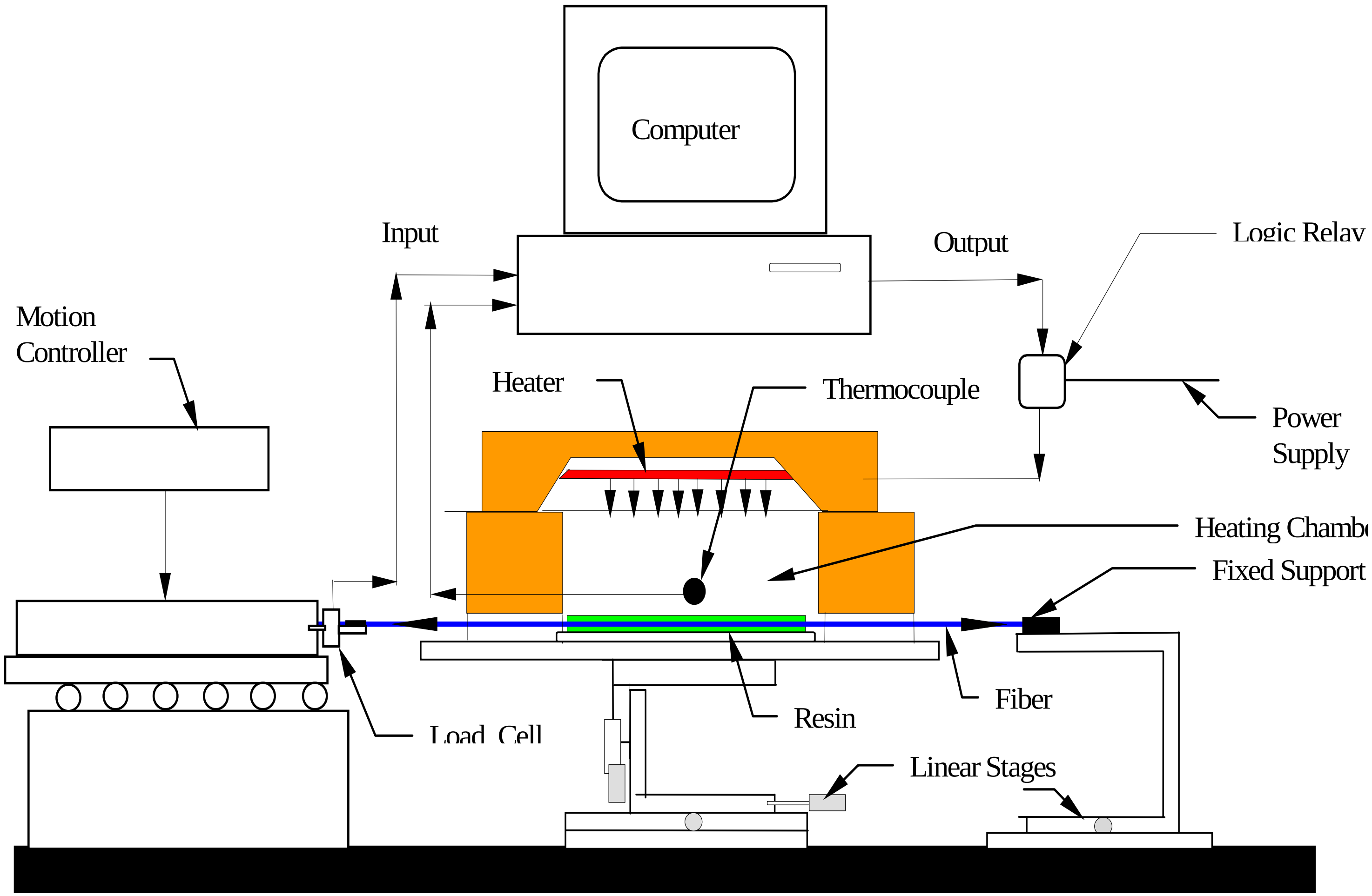
Vitrification Occurs At End of Cure Cycle, Prior to Cooling



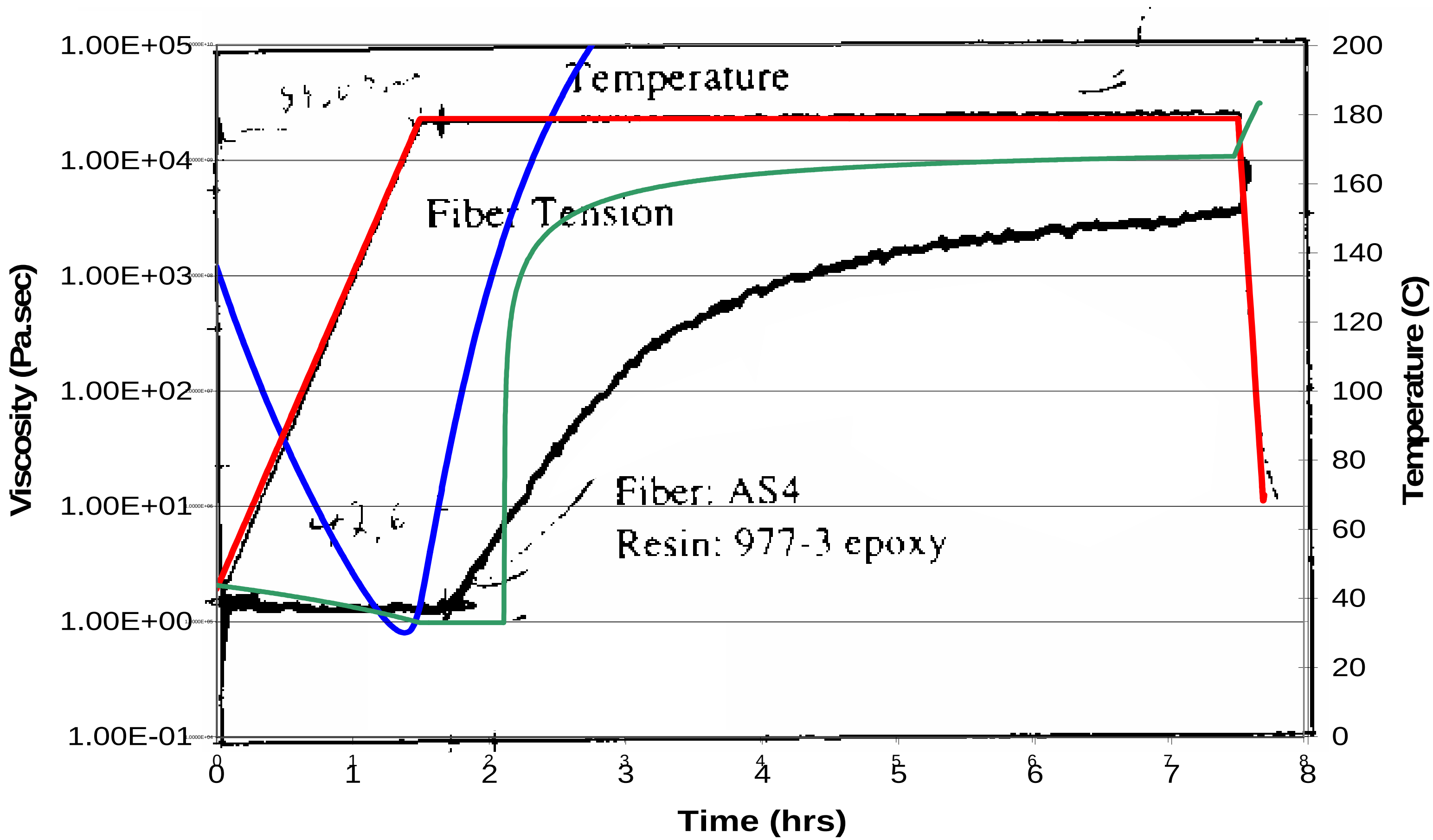
Schematic of CIST Apparatus

(cure-induced stress test)

University of Tennessee, Madu Madukar

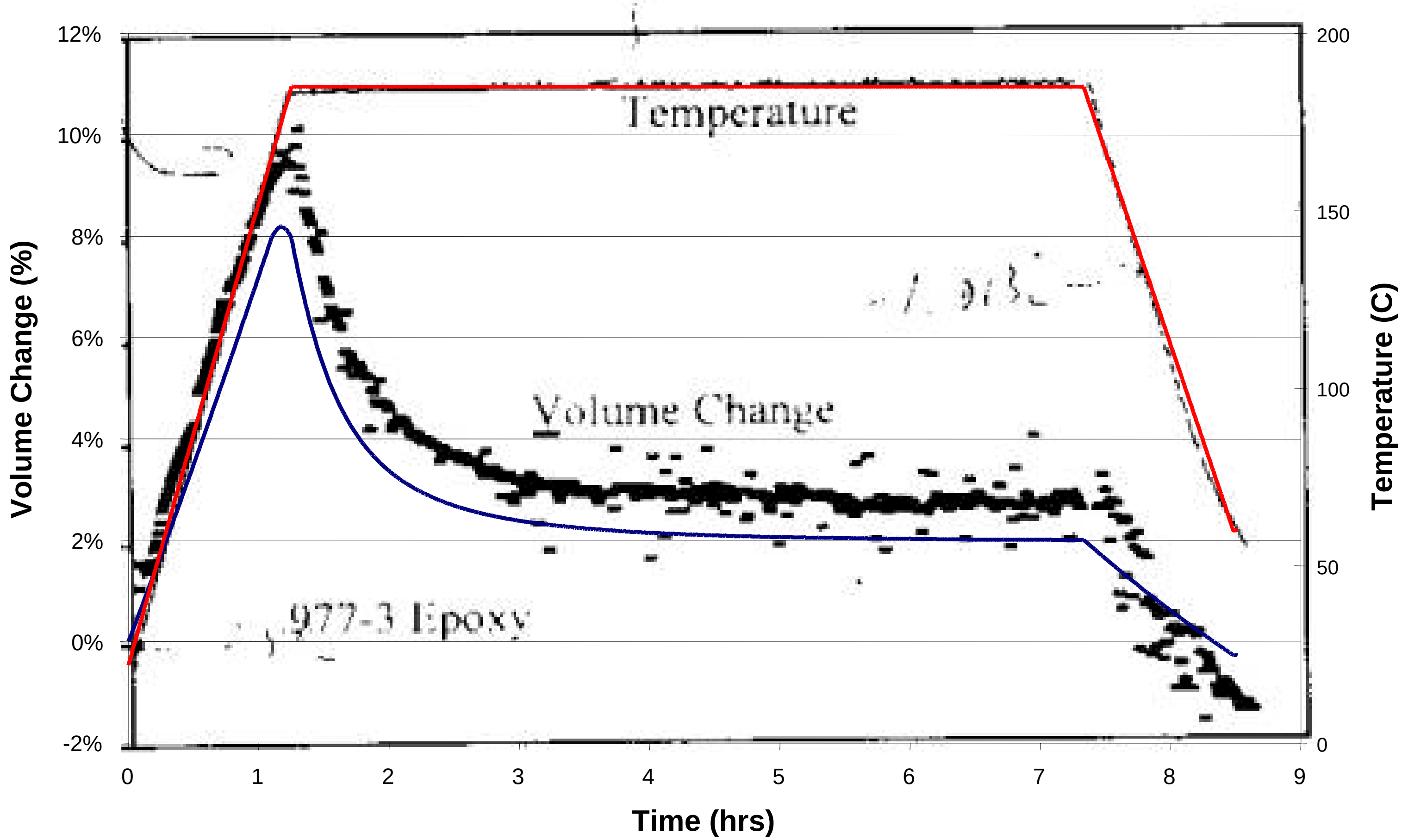


Gel Point is Consistent
Although Magnitude Needs Study



Data From Genidy, Madhukar, and Russell, Journal of Composite Materials, Vol. 34, No. 22/2000

Cure Shrinkage Effect is Consistent with Published Work



Data From Genidy, Madhukar, and Russell, Journal of Composite Materials, Vol. 34, No. 22/2000

Sample Problem 2

Zero CTE Structure

Problem Statement

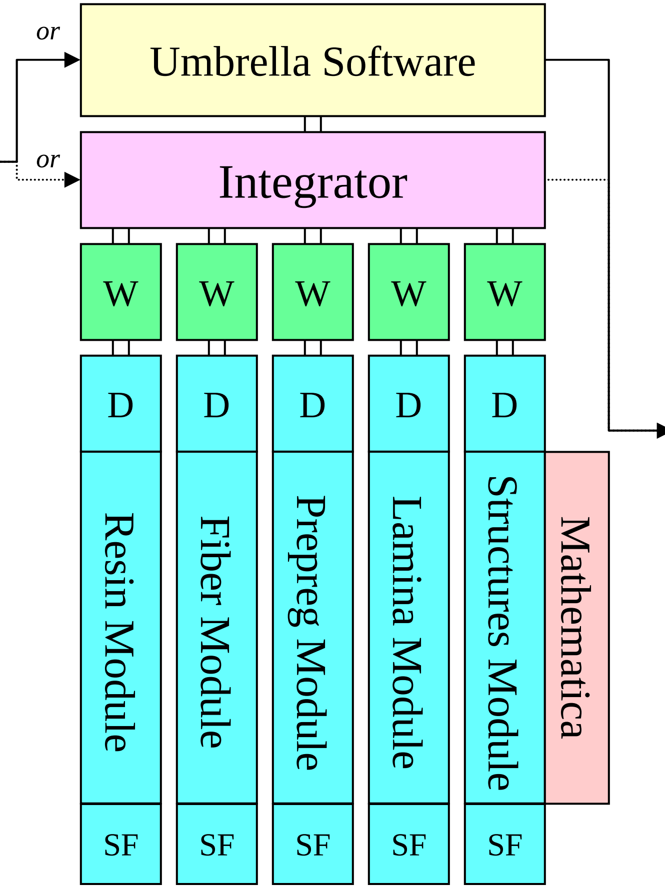
- Zero CTE composites are often used in applications needing thermally stable structure.
- A zero CTE laminate is produced by using low or negative CTE carbon fiber laminates.

Determine a layup (fiber angle stacking sequence) that would give you a zero CTE laminate.

System Architecture

Input Variable
Temperature
Degree of Cure
Lay-up Definition

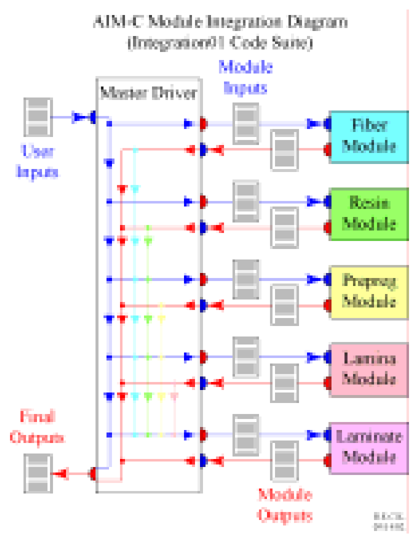
Residual Stress State*



All Resin Properties
All Fiber Properties
All Prepreg Properties
All Lamina Properties
Laminate Physical Properties:
- Density of Laminate
- Longitudinal CTE
- Transverse CTE
- Shear CTE
- Through Thickness CTE
- Longitudinal CTE
- Transverse CTE
- Shear CME
- Through Thickness CME
- Longitudinal Thermal Conductivity
- Transverse Thermal Conductivity
- Through Thickness Thermal Conductivity

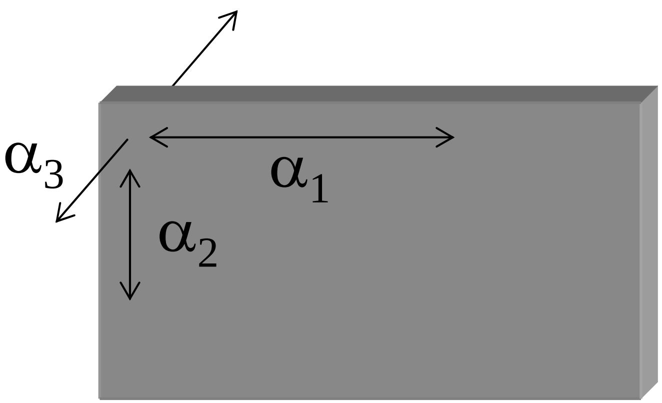
Mechanical Properties:
- Stiffness Matrix
- Coupling Matrix
- Bending Matrix

Strength Properties:
- Longitudinal Tensile Strength
- Longitudinal Compressive Strength
- Longitudinal Open Hole Tensile Strength
- Longitudinal Open Hole Compressive Strength



Assume an Eight-Ply Laminate

Made of 0's, and +/- θ Angles
Built Symmetrically



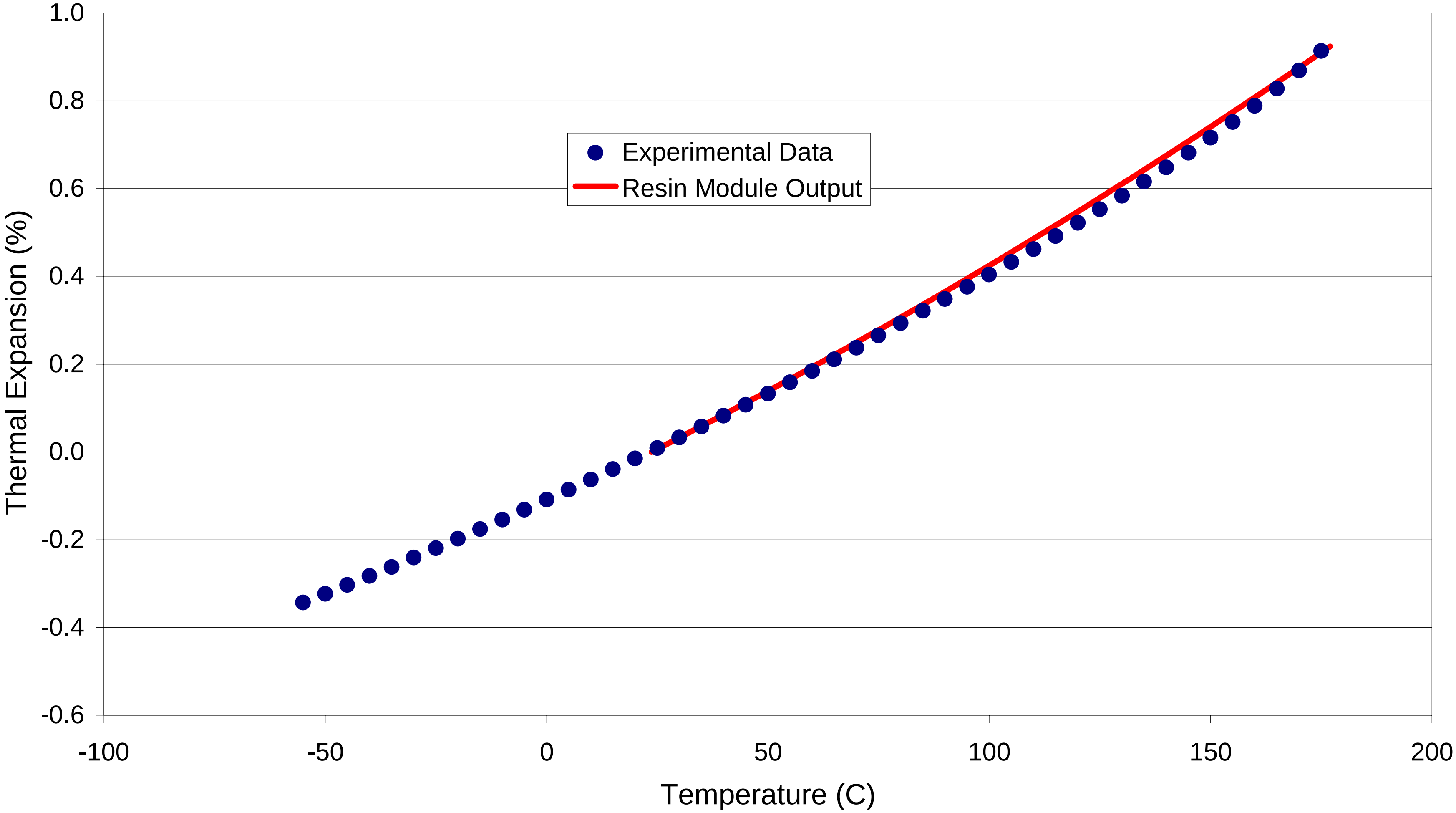
Ply Number	Layup 1 $[+\theta,-\theta]4s$	Layup 2 $[+\theta,-\theta,0,+\theta,-\theta,0, +\theta,-\theta]s$	Layup 3 $[+\theta,0,-\theta,0,+\theta,0,-\theta,0]s$	Layup 4 $[0,0,+\theta,0,0,-\theta,0,0]s$	
1	$+\theta$	$+\theta$	$+\theta$	0	
2	$-\theta$	$-\theta$	0	0	
3	$+\theta$	0	$-\theta$	$+\theta$	
4	$-\theta$	$+\theta$	0	0	*sym*
5	$+\theta$	$-\theta$	$+\theta$	0	
6	$-\theta$	0	0	$-\theta$	
7	$+\theta$	$+\theta$	$-\theta$	0	
8	$-\theta$	$-\theta$	0	0	

θ was varied from -10º to +90º in steps of 5º.

Resin Module Captures Resin CTE

Property from fully cured neat resin

Behavior Dependant on Temperature and Degree of Cure



Fiber Module Captures Fiber CTE

Behavior Dependant on Temperature and Degree of Cure

$\alpha_1 = -2.22E\text{-}7$ Axial

$\alpha_2 = 1.118E\text{-}5$ Transverse

Fiber Module Text Output

FIBMOD_SETUP.out - Notepad

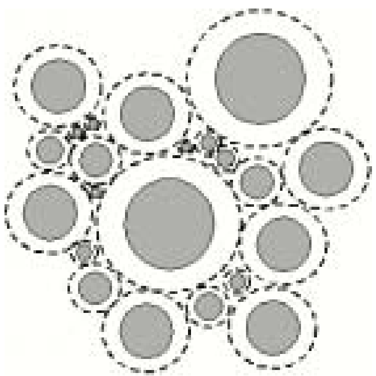
File Edit Format Help

```
Fiber Property = Value Units
Fi_E_1 =  2.7700000027E+11 Pa
Fi_E_2 =  1.7200000208E+10 Pa
Fi_G_12 =  1.8600000000E+10 Pa
Fi_G_23 =  4.8300000000E+09 Pa
Fi_nu_12 =  2.0000000000E-01 unitless
Fi_nu_23 =  2.5000000000E-01 unitless
Fi_Snf_1 =  1.8180000035E-02 unitless
Fi_Ssf_1 =  4.9500000110E+09 Pa
Fi_rho =  1.7810000004E+00 g/cc
Fi_Cp =  9.3022617815E+02 J/kg.K
Fi_k_1 =  5.2813479194E+00 W/m.K
Fi_k_2 =  1.2195054698E+00 W/m.K
Fi_alpha_1 = -2.2200000000E-07 1/K
Fi_alpha_2 =  0.0000000000E+00 *no input data*
Fi_Yield =  4.4596000030E-01 g/m
Fi_Dia =  5.0000000000E-09 m
Fi_Count =  1.2000000000E+01 K
Fi_Eb_2 =  0.0000000000E+00 *no input data*
Fi_ScC_1 =  3.3230000000E+09 *no input data*
Fi_Cost =  5.0000000000E+01 $/lb
Fi_Ssf_2 =  1.1000000000E+08 Pa
Fi_Ssf_12 =  1.1700000000E+08 Pa
Fi_Ssf_23 =  8.2700000000E+07 Pa
```

Lamina and Laminate Modules

Effects of Resin Fiber and Prepreg Properties

- **Composite Cylinders Assemblage used for lamina thermoelastic property prediction.**
- **Laminated plate theory for $[((0/90)_S)_2]_S$ laminate level properties.**
- **Laminate analyses conducted using closed-form solution for stresses near an open hole.**
- **Various Failure Criteria (Max Strain, Hashin Interaction and PASS) can be compared.**



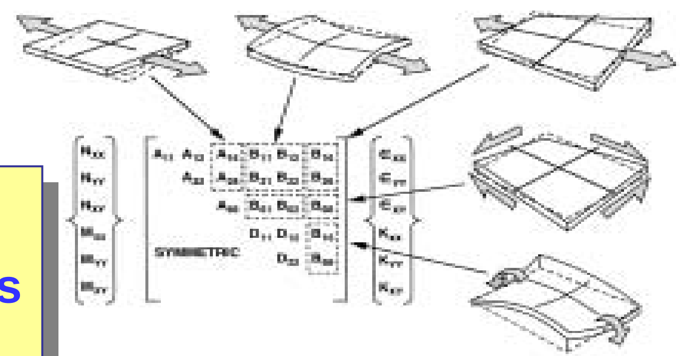
Models for Continuous Fiber Composites

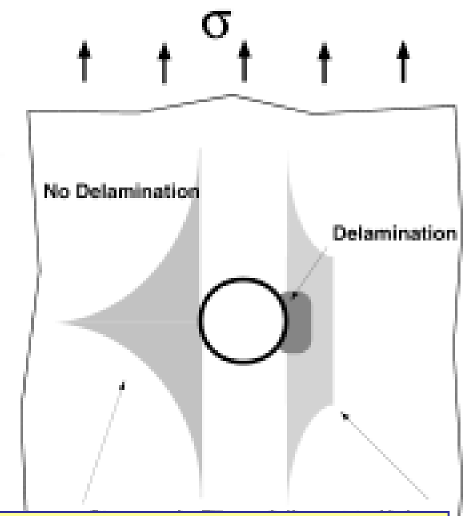
Composite Cylinders Assemblage (CCA)

Generalized Self-Consistent Method (GSCM)

Models for Effective Continuum Properties

Classical Lamination Theory (CLT)





Models for Predicting Structural Response

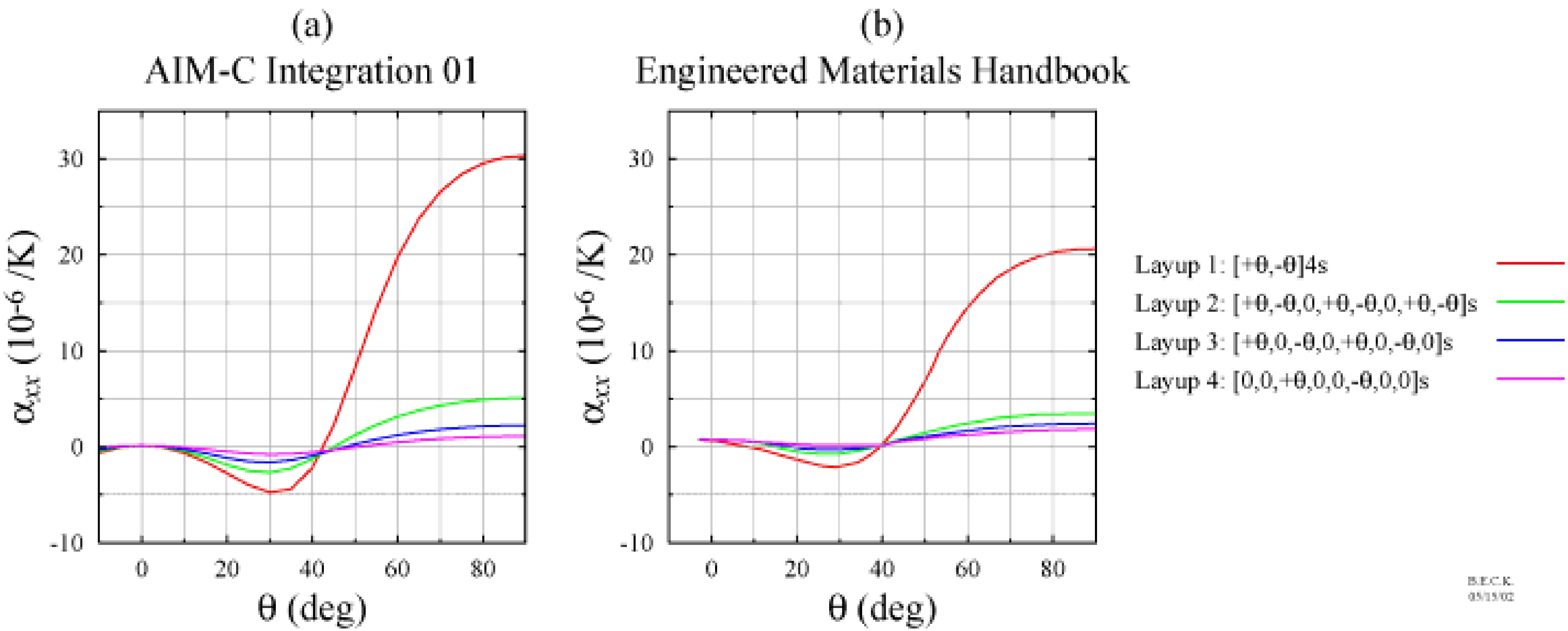
Level 1 : Parametric Analyses; elastic laminate with approximations

Results of Analysis

Two Solutions, at ~0-deg, and ~43-deg

The difference in solutions is due to resin and fiber type

Layup 4 with θ = 49-deg gives a "robust" solution



(b) ref. Principe, F. S., Manib, M.M., and Linsenmann, D. R., Design Requirements, pp 181 – 184, in Engineered Materials Handbook, Volume 1, 1987 Composites, ASM International.

Sample Problem 3

Cure of Thick Laminates

Cure Cycle Development

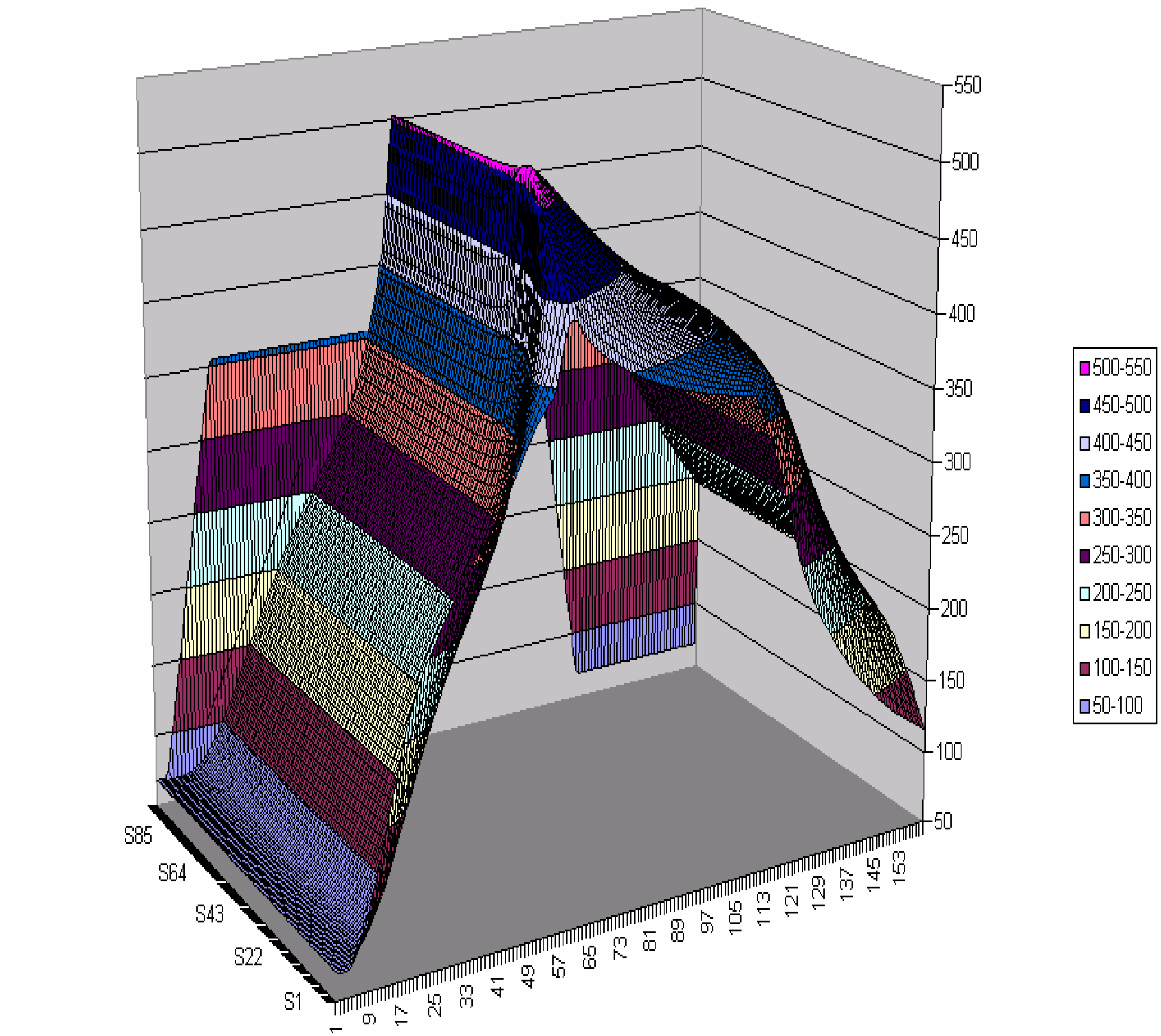
Problem Statement

- The heat of reaction during cure can create extremely high temperatures, especially in thick laminates.
- Autoclaves heat transfer characteristics vary greatly, compounding the problem.

Develop a robust cure cycle for a thick laminate, given inherent variability due to heat transfer.

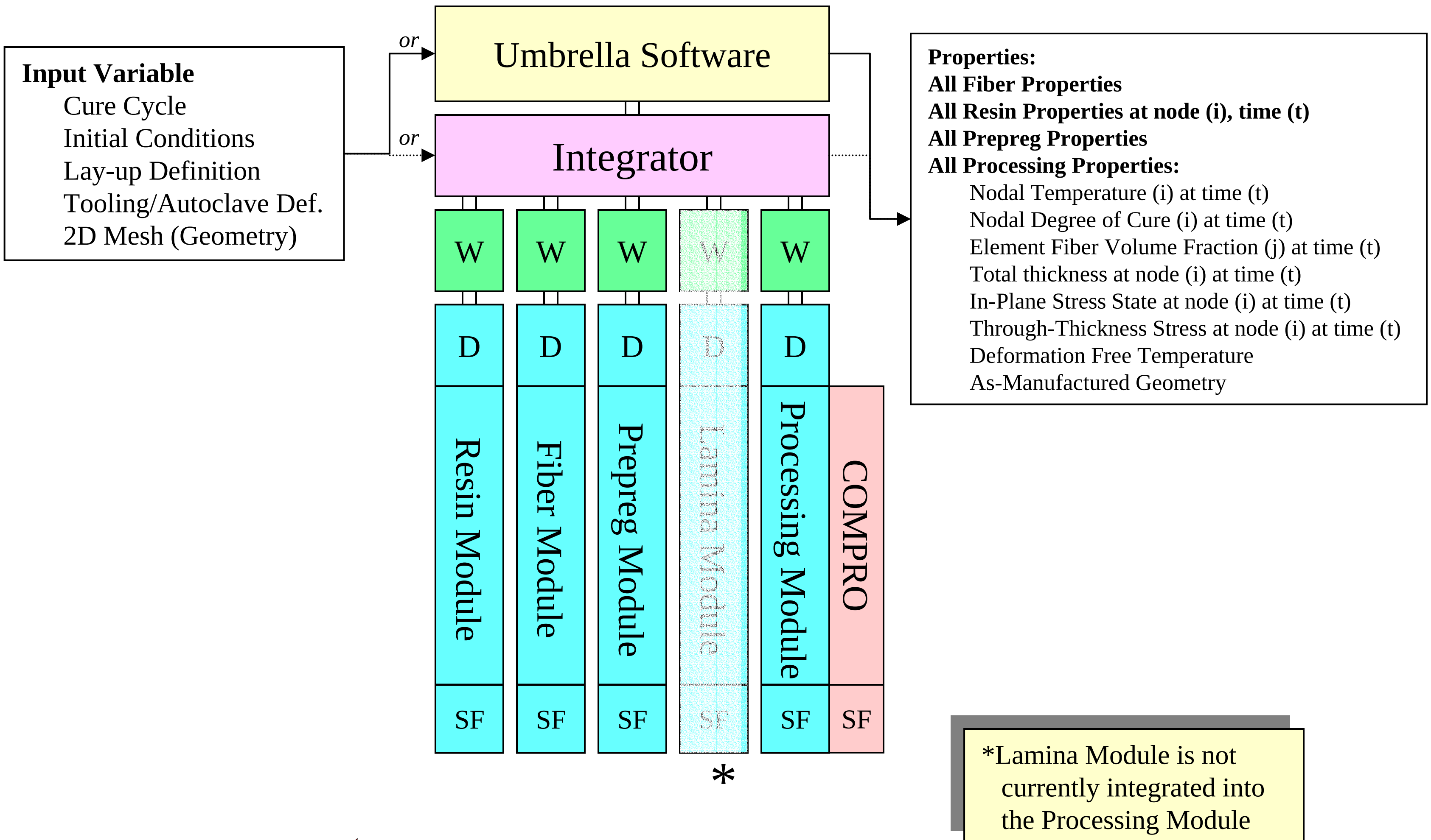
Example of Problem

977-3/IM7 - 5-inches thick

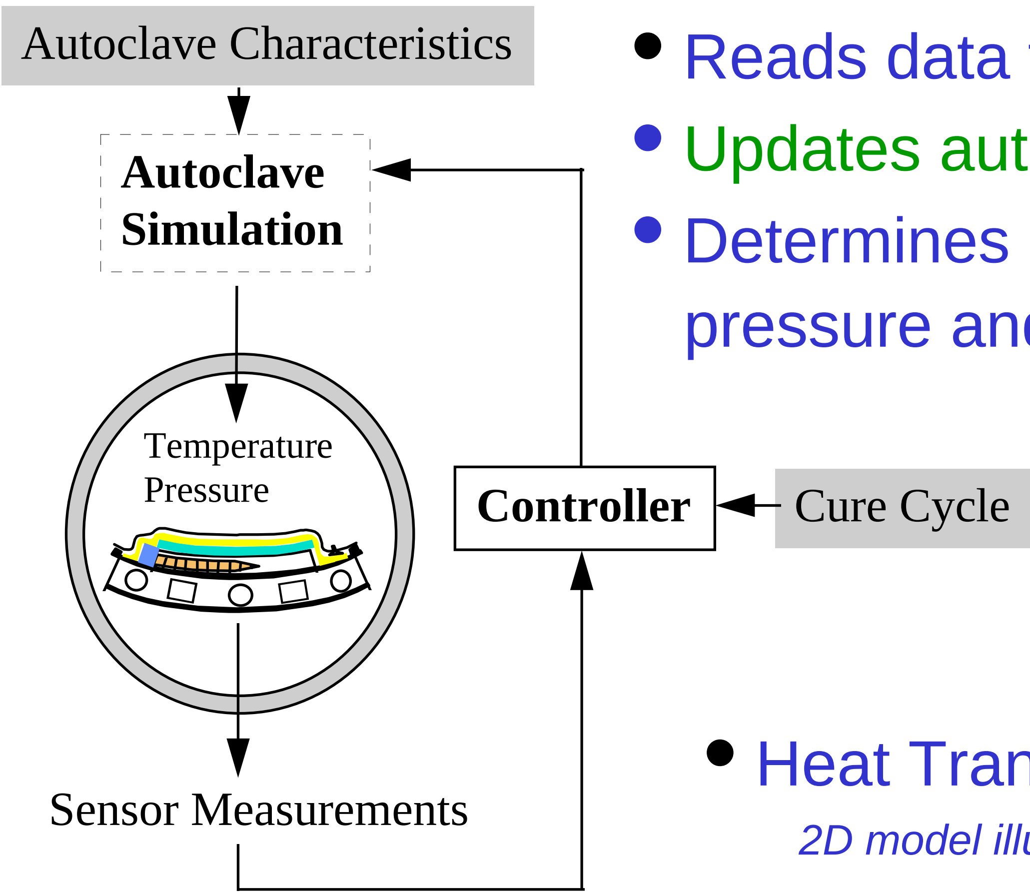


System Architecture

Processing Properties



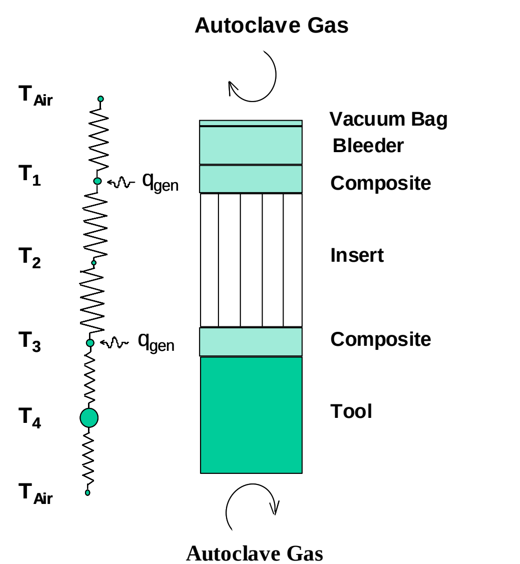
Model of the Autoclave



- Reads data from "virtual sensors"
- Updates autoclave controller set points
- Determines autoclave temperature, pressure and bag pressure

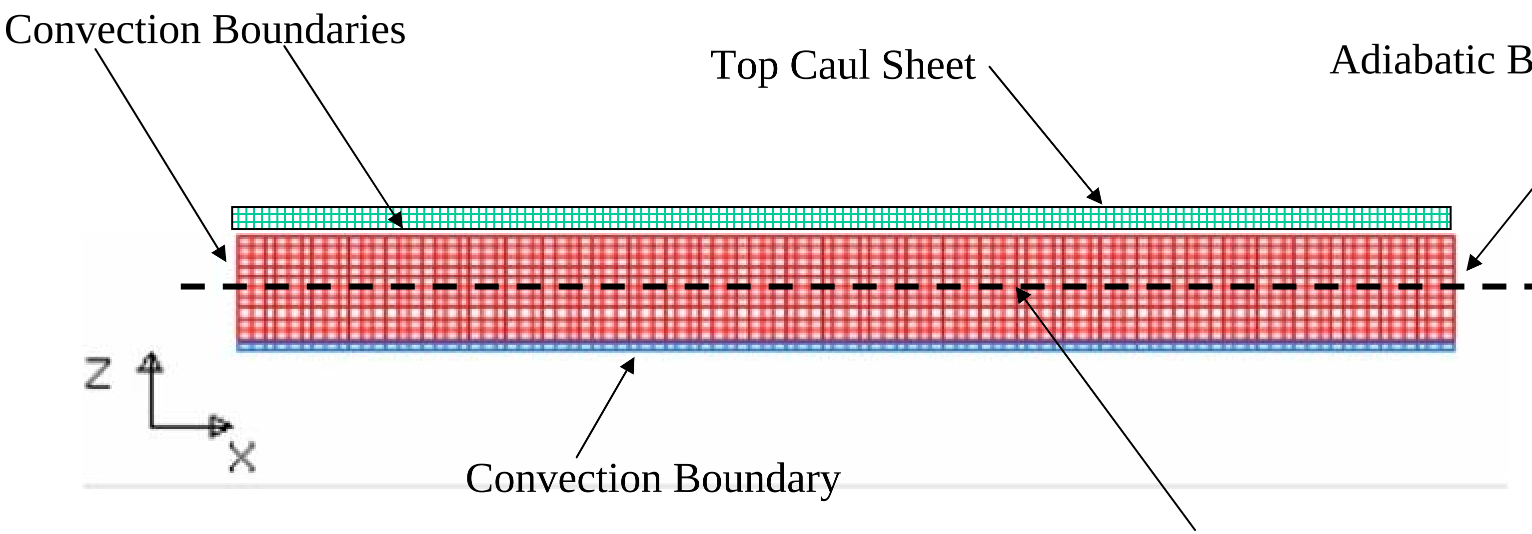
- Heat Transfer

  2D model illustrated in 1-D



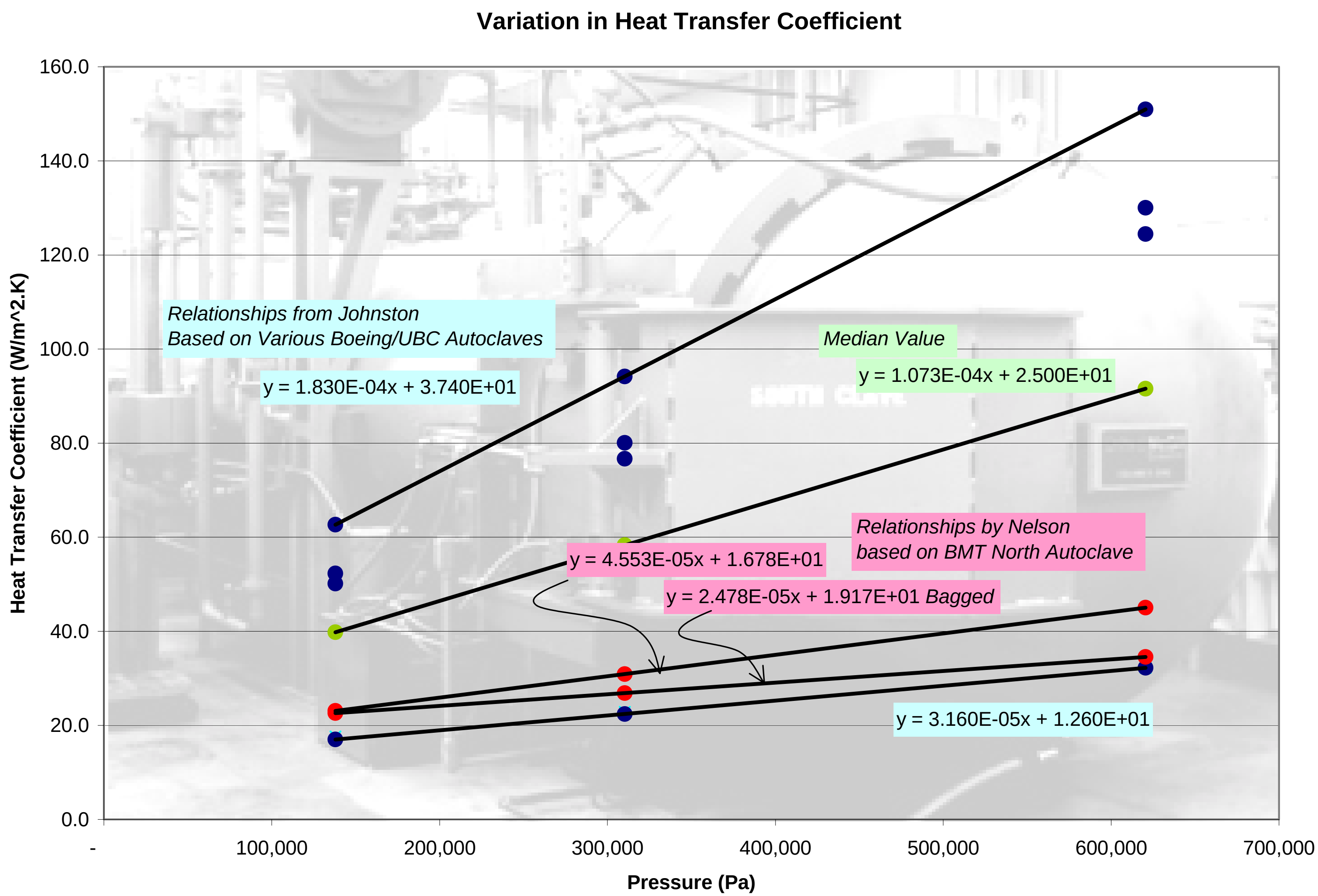
AIM Processing Module

5” thick part on 0.5” thick Invar tool



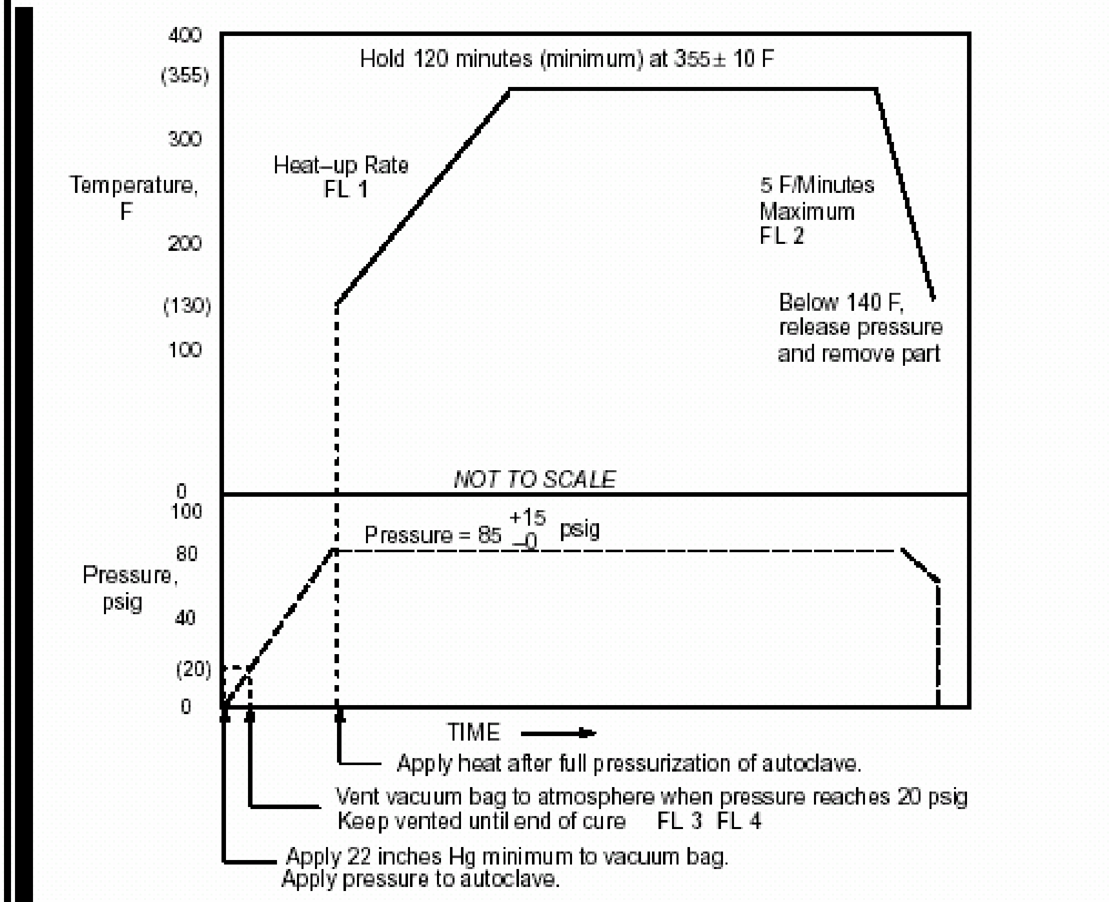
- Look at part temperature with respect to time and position along center line

Heat Transfer Variability



Process Specification

******* PSDS GENERATED *******



FL 1 Heating rate requirements apply only from 130 to 345 F and are as follows:

Temperature Range	Heat–up Rate
130 to 300 F	1 to 5 F/minute
301 to 330 F	0.3 to 5 F/minute
331 to 345 F	0.1 to 5 F/minute

Base-Line 4.25 deg F/min

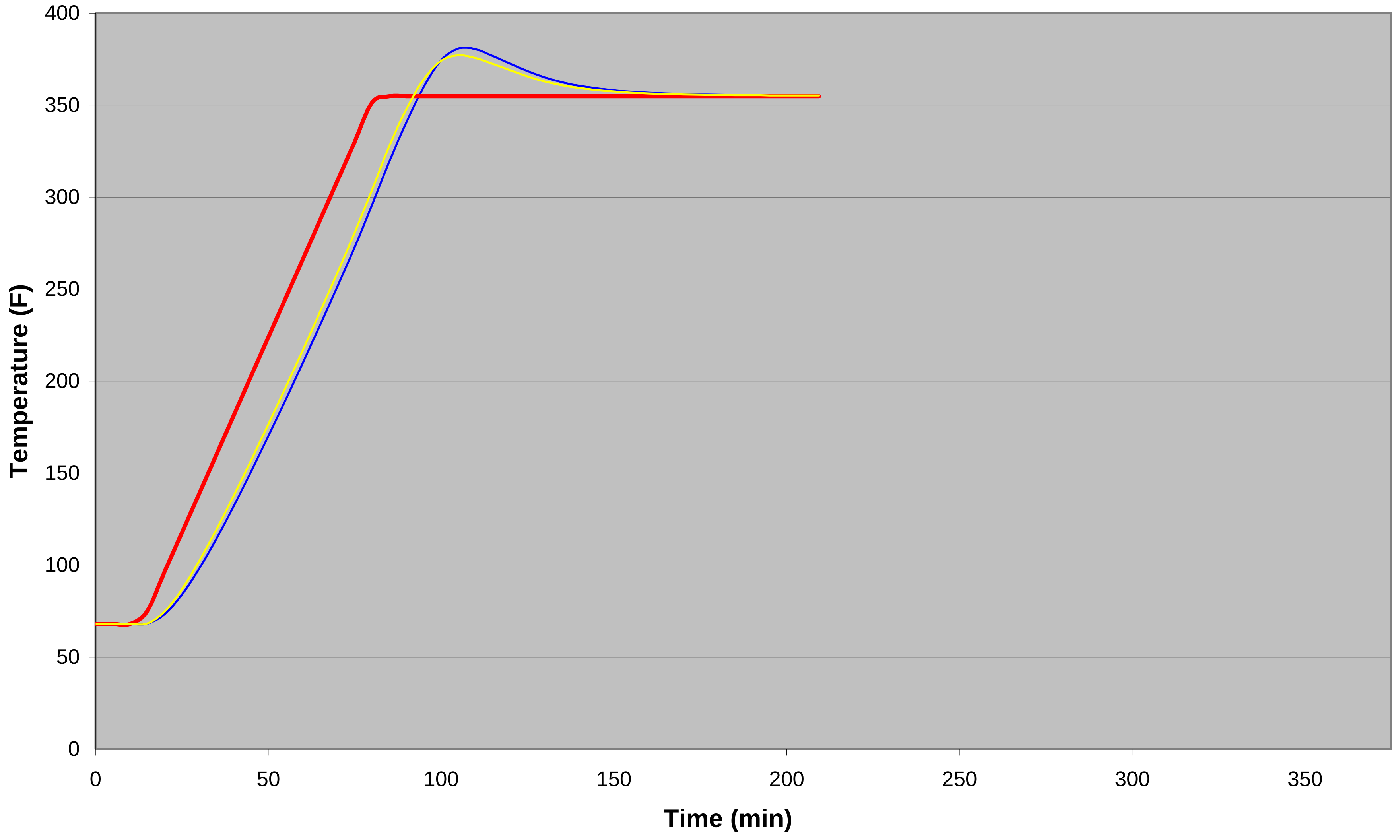
Setting up and Solving a Problem

Benchmark

Advanced User *(Karl Nelson)*

Reviewing Specifications and Background Info	2-hrs
Defining Geometry	1-hr
Trouble Shooting	2-hrs
Running Simulations and Reviewing Results	5-hrs
Review Final Results with Customer	½-hr
Total Time	10 1/2-hrs

Cure of 0.88-inch Thick Laminate Simulation of Typical Cure Cycle

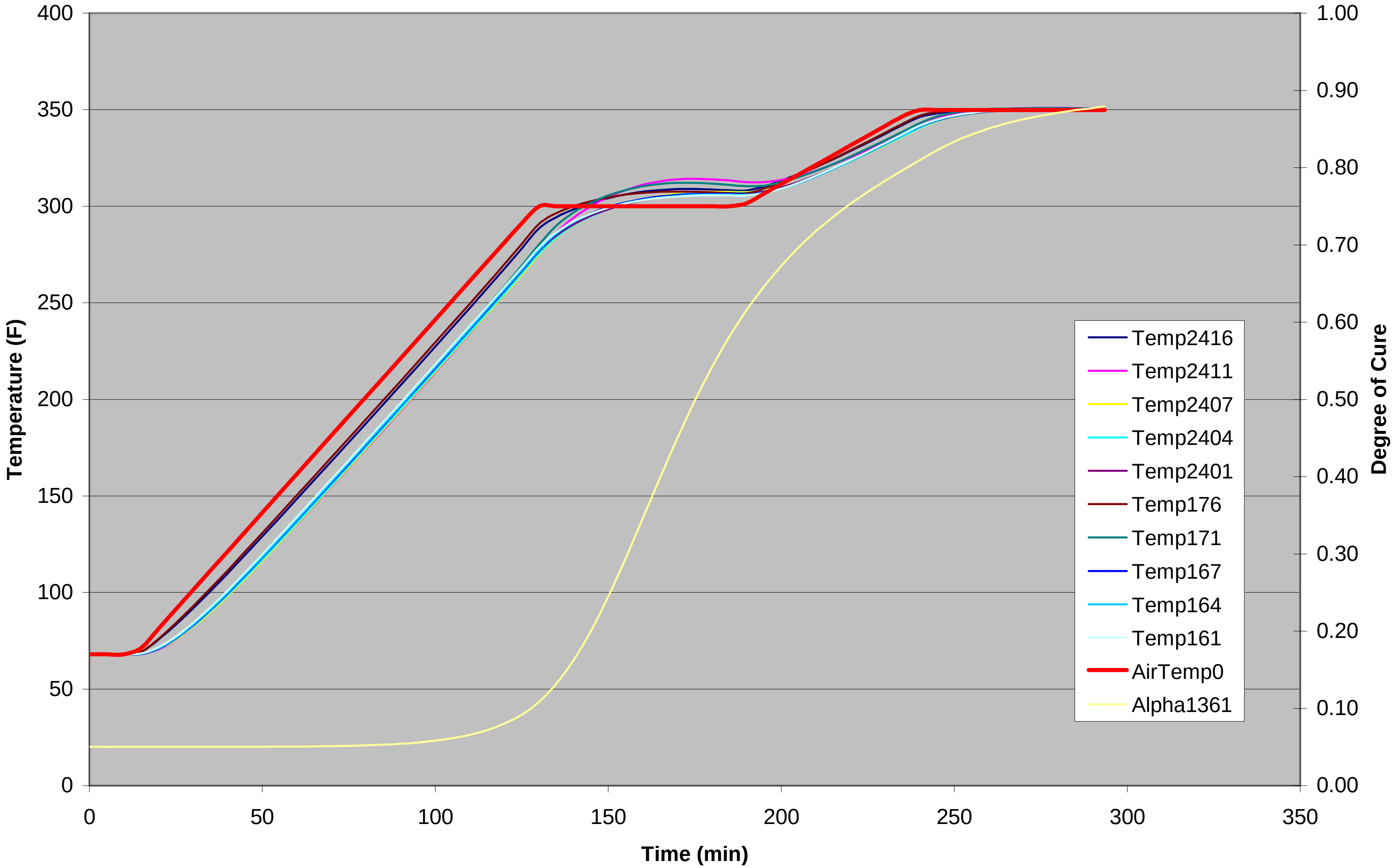


Engineering Recommendation

Based on Processing Module (COMPRO) Results

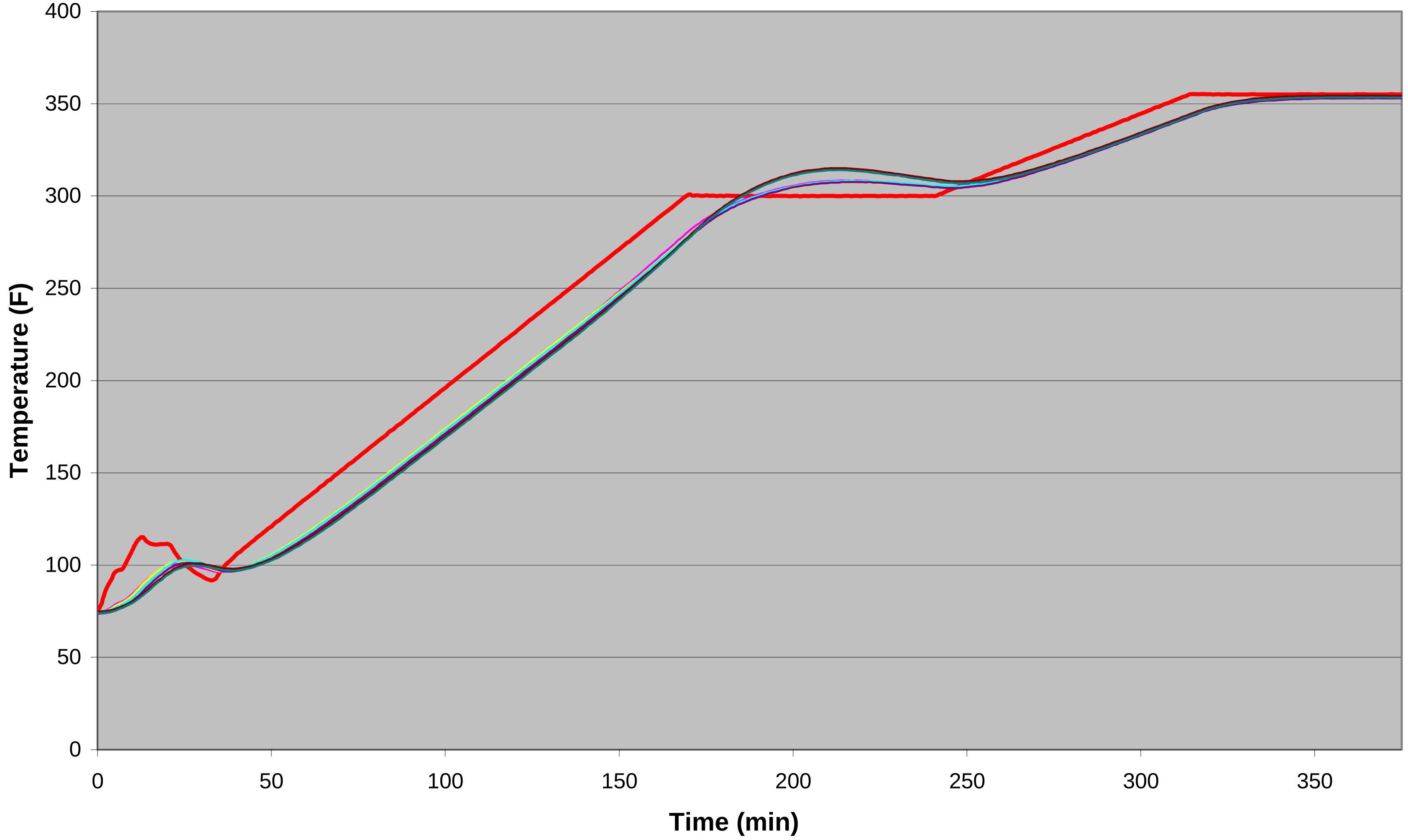
1. Heat at a maximum heating rate (based on air thermocouple) of 2F/min up to a 300 +/- 10F hold.
2. Hold at 300 +/- 10F for a minimum of 60-minutes.
3. Heat at a maximum heating rate of 1F/min to a target of 350F (350+15/-5)
4. Hold base on the lagging part thermocouple for 120-min (as prescribed in processing specification).
5. Complete the cycle as put forth in processing specification.

Predicted Response of 0.88-inch Thick Carbon/Epoxy Laminate



The heat transfer coefficient was unknown, so the challenge was to develop a (robust) cycle that would be work no matter what the value.

Autoclave Thermocouple Data of 0.88-in Thick Carbon/Epoxy Laminate



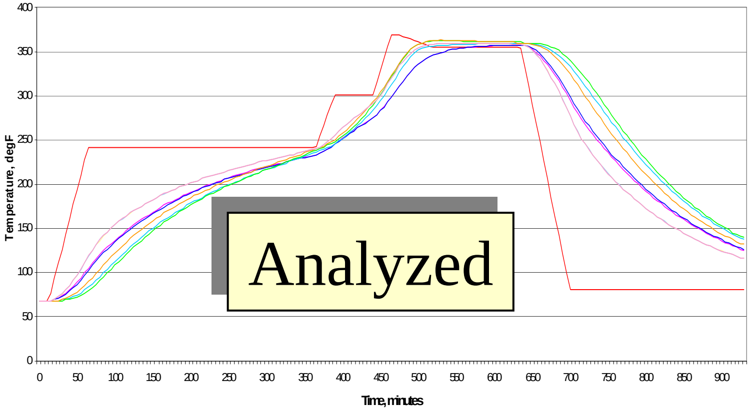
Problem Solution of John Kooch

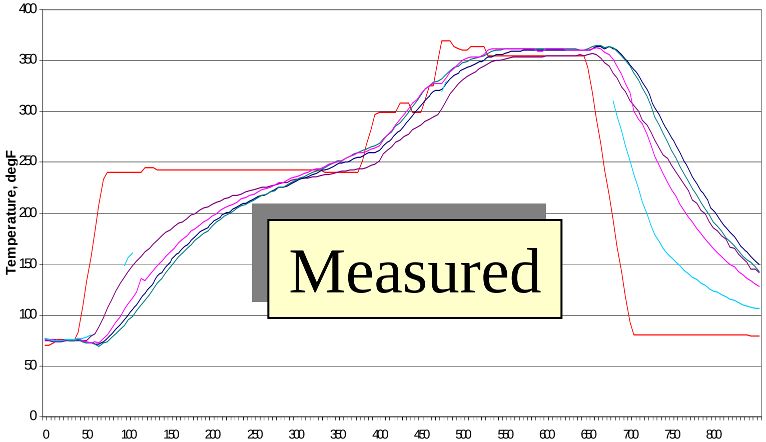
Can We Cure a Laminate up to 5-inches?

- Process design by analysis – validate by test
- Carbon/Epoxy
- Current simulations indicate *yes*
- Test run just completed at Boeing MR&D in Auburn
  - 3.5-inch thick laminate 18-inch square.

Successful Cure of 3 ½ inch Thick Laminate

First Time - Using Analysis To Specify Cure Cycle





More Complex Problems

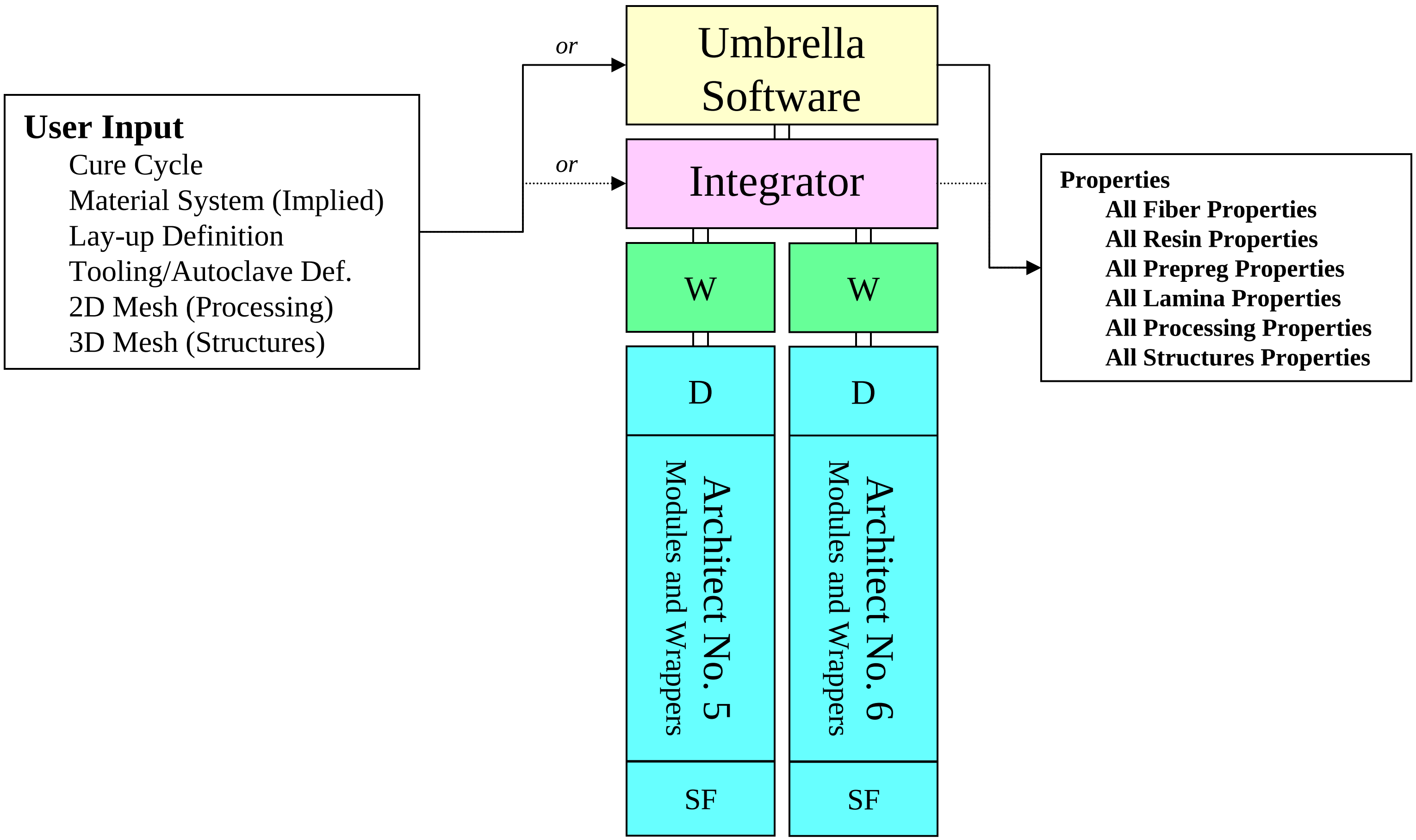
- How do you use the tools to design and build a complex composite structure?
- Can you accurately predict failure and the failure mode:

Demonstrate capability with the design of a hat-stiffened panel -- Currently being worked as our part of our validation/demonstration

Architecture

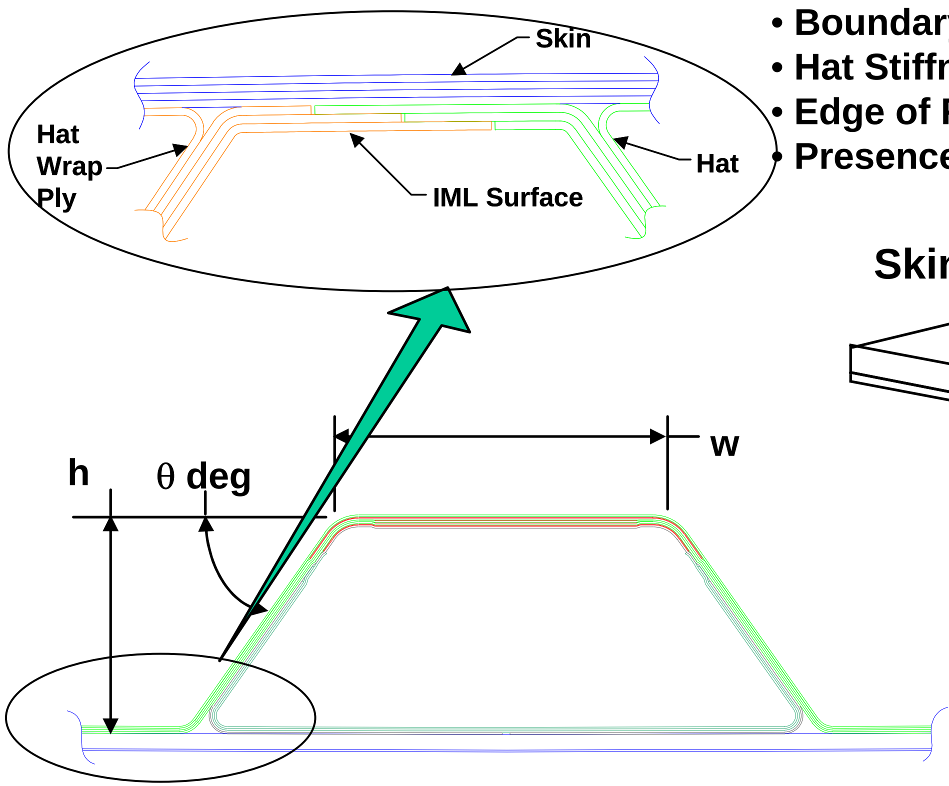
Strength Properties

Residual Stress State from Processing Module

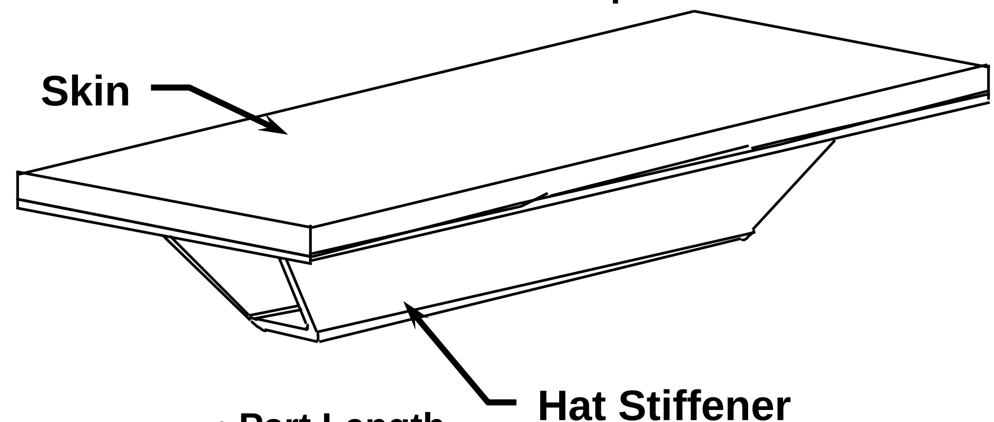


Understanding The Mechanics of a Stiffener Runout
A True 3D Problem with Hundreds of Variables

- Runout Shape and Angle
- Boundary Conditions/Edge Reinforcement
- Hat Stiffness Tailoring at/near Runout
- Edge of Flange Configuration (Tapered, Square-edged)
- Presence or Absence of Internal Wrap Plies



Sect A-A



- Part Length
- Skin Thickness
- Spanwise/Chordwise ply dropoffs
- Hat Geometry (e.g., h, w, and θ)
- Layups
- Taper?

Comments and Summary

- Accelerated Insertion of Materials Can be Achieved by
  - Definition of requirements
  - Focus based on insertion needs (DKB)
  - Approach for use of existing <u>**K**</u>nowledge
  - Validated <u>**A**</u>nalysis tools
  - Focused <u>**T**</u>esting
  - Feature Based Demonstration
  - Rework Avoidance
  - Knowledge management

AIM-C Alignment Tool

The Objective of the AIM-C Program is to Provide Concepts, an Approach, and Tools That Can Accelerate the Insertion of Composite Materials Into DoD Products

AIM-C Will Accomplish This Three Ways

Methodology - ***We will evaluate the historical roadblocks to effective implementation of composites and offer a process or protocol to eliminate these roadblocks and a strategy to expand the use of the systems and processes developed.***

Product Development - ***We will develop a software tool, resident and accessible through the Internet that will allow rapid evaluation of composite materials for various applications.***

Demonstration/Validation - ***We will provide a mechanism for acceptance by primary users of the system and validation by those responsible for certification of the applications in which the new materials may be used.***